COMBUSTION

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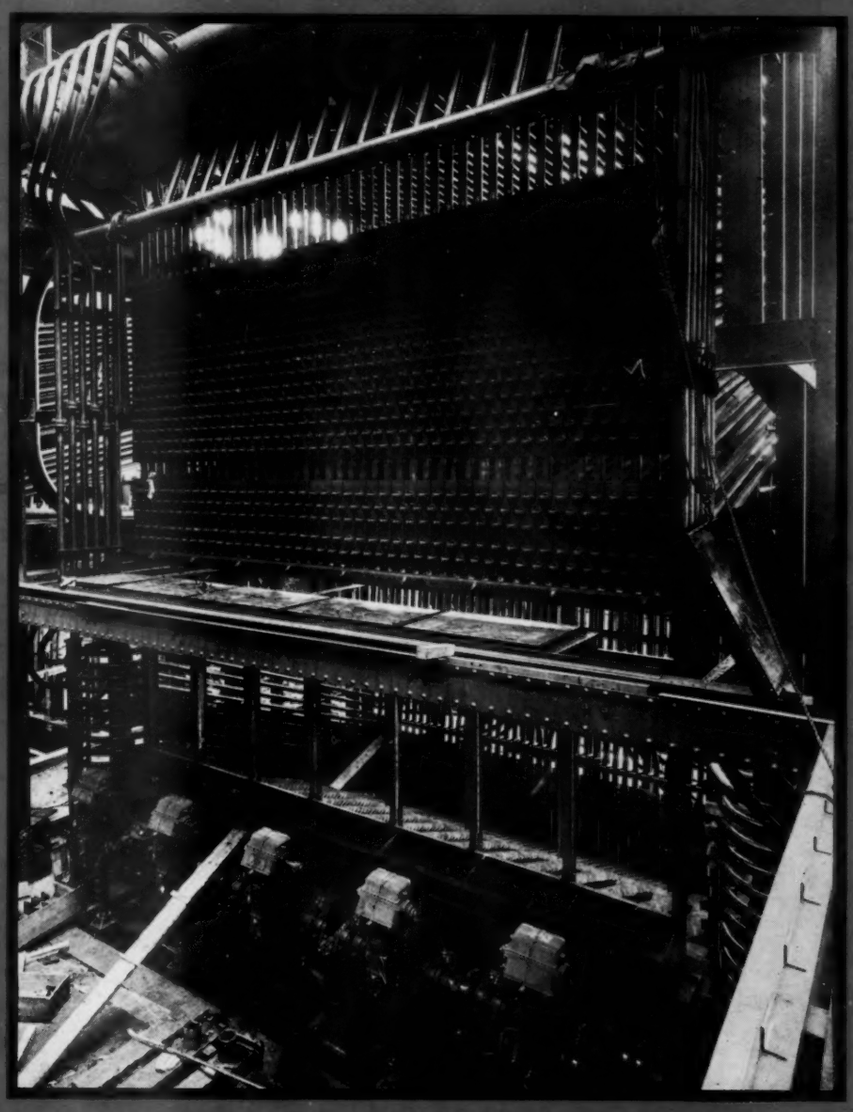


Boilers and stokers being installed at new central heating plant for federal buildings, Washington, D. C.

Design Features of the Port Washington Power Plant

Experiments Regarding Circulation in Vertical-Tube Boilers

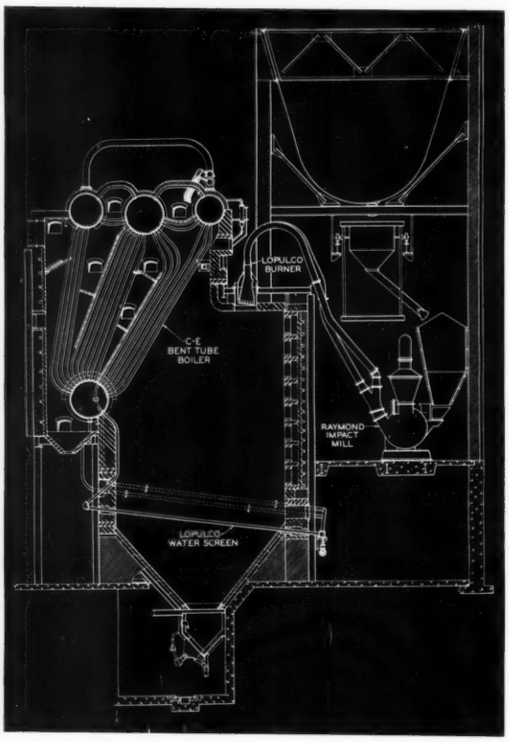
2,120,000* Sq. Ft.

of boiler heating surface equipped with the

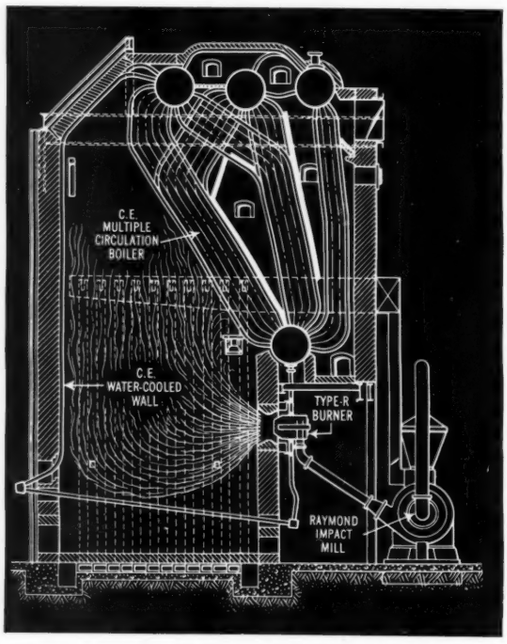
LOPULCO

DIRECT-FIRED SYSTEM

for burning pulverized coal



Lopulco Direct-Fired System as applied for vertical firing to a 616 hp. C-E Bent Tube Boiler. This is one of three identical units in a plant which recently-published operating figures indicate to be the most efficient industrial plant in the country.



Lopulco Direct-Fired System as applied for horizontal firing to a C-E Multiple Circulation Boiler. Size of boiler—approximately 400 hp.

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*American plants only. Many installations have been made in foreign countries.

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COMBUSTION

VOLUME FIVE • NUMBER TWO

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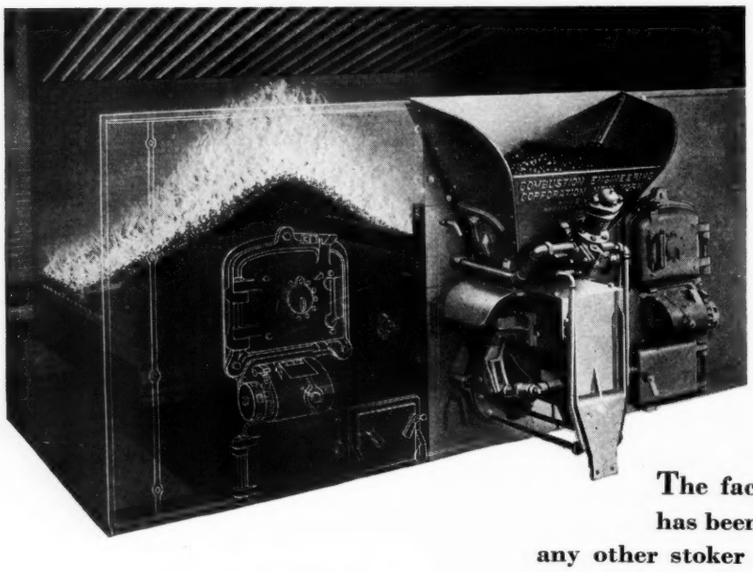
11,635,000* Sq. Ft.

of boiler heating surface equipped with



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EDITORIAL

A Time for Action

TODAY, all we need to do is to face facts to know that business recovery is a *fact*. Of course, there may be some leveling off in the upward trend, but the tremendous forward movement that is apparent in all industries is not going to reverse itself or suddenly peter out. The accumulated needs of three years of depression cannot be adequately satisfied for a long time to come and, in the meantime, the general trend, supported by increasing employment at higher wage scales with corresponding improvement in mass buying power, is going to continue upward.

This then is the situation confronting us, but things have been happening so fast in the past two months that most of us are finding it very difficult to get a good perspective on our immediate problems. Whatever the fundamental justification for it, however, we all instinctively know that this is a time for action—that we can no longer afford merely to think about things we might do or ought to do in order to gear ourselves into the rapidly moving machinery of recovery.

Swinging this viewpoint into focus on the power plants of the country, we find a scene of encouraging activity. Loads have increased materially. Spare units are being rapidly overhauled and made ready for service. Many plant engineers are already engaged with plans for revamping present equipment or installing new equipment to achieve greater efficiency and economy or to bring capacity up to anticipated load requirements, and many others are well started on preliminary studies on ways and means of accomplishing these ends. There are still others, however, and a considerable number of them who, while doing their daily job well, have as yet developed no definite plans for plant improvement.

To the latter group this editorial is particularly addressed. To these engineers, many of whom may have the excuse of not yet having seen any sign of executive encouragement in matters that involve expenditure, we suggest the thought that the new order of things, industrially speaking, will bring with it new opportunities for those who exercise initiative. Industry, more than ever before, must find its profits in operating economies, and management will expect those who best know the whys and wherefors of its operations to take the initiative in cost-reduction programs.

In no department of industry are there more tangible opportunities for substantial dividends from moderate investments than in the boiler room. Relatively few industrial plants produce steam economically, judged by present-day standards. Developments of recent years make it not only possible but entirely practicable for comparatively small boiler plants to operate at efficiencies closely approaching those obtained in large central stations. This statement does not have to be taken at its face value. It is a very simple matter to verify it.

Management can no longer afford to overlook savings that will pay off the required investments in one, two or three years. The new industrial economy demands that such opportunities be realized upon without delay. The practical standardization of labor rates and other factors affecting operating costs will give such possibilities for savings an importance and interest to management that assure their proper consideration.

And so we say to the engineers who are still just thinking about these things—*this is a time for action.* Forget the fact that the boss has for a long time past shown a marked disinterest in spending money to save money, and make a fresh start. We believe you will find him in a mood of surprising receptiveness to facts and figures that indicate possibilities of substantial savings, and it will cost you nothing but time and effort to get them. Don't let some one else do the job and get the rewards that are rightfully yours.

Are the Utilities Overbuilt?

UNTIL recently we shared the quite general opinion that they were to a rather considerable extent, at least sufficiently to make it unnecessary to add any substantial amount of generating capacity for two years or perhaps more.

Like other opinions we had entertained quite seriously until the startling developments of the first half of 1933 forced us to do an "about face"—for instance, our conclusion that prohibition repeal would take years to accomplish—this one is wavering so unsteadily that some reconsideration of it seems immediately necessary.

Here's the situation as we now see it. According to figures published in the July 29 issue of *Electrical World*, additions to generating capacity since 1929 aggregate 3,500,000 kw. In 1929, surplus capacity was no more than normal for the industry. Since then there has been an increase of connected load, due to sales of lights, appliances, motors, etc., amounting to approximately 42,000,000 kw. This means an increased demand on generating capacity of approximately 4,200,000 kw. Principally because of this new load, electrical output in 1932 was only 15 per cent less than in 1929.

The rapid pick-up the last three months is common knowledge. At present, output is nearly 95 per cent of the 1929 rate. Domestic and retail sales which have increased steadily during the depression years will continue to increase. The industrial load is increasing at a rate which indicates the passing of 1929 total figures in the near future.

When it is considered that utility projects require from one to three years from the time work is started on the drafting boards until the new capacity becomes available, certainly there is much reason to believe that the utilities will shortly begin to plan extensions.

In so far as steam plant equipment is concerned, considerable additional capacity can be obtained by remodeling the less efficient plants of a system either by modernizing present boiler units or using them as standby and installing large modern units to carry the principal part of the load. We are inclined to think that there will be quite a lot of this kind of work undertaken by the larger systems not only to provide additional capacity but also to improve the overall economy of the system. In the smaller systems, we expect to see additions to present plants and, in some cases, the building of new plants in rapidly growing load centers.

Reviewing the entire situation, we predict the initiation this fall of plans for the modernization and extension of utility generating facilities on a scale that will mean considerable equipment buying.

Experiments Regarding Circulation in Vertical-Tube Boilers*

By Dr.-Ing. ERNST SCHMIDT, Danzig, Poland

In the laboratory of the Technical High School, Danzig, the running ahead of the steam bubbles were investigated in tubes of 20.3 ft. length and of 2.25 in., 2.7 in. and 3.25 in. i.d., with various steam quantities and for pressures up to 570 lb. per sq. in. It was shown that the relative velocity rose materially with reduction in specific weight of the mixture, or with increased steam content, but dropped considerably with rising pressure. The tube diameter proved to be a small influence within the limits of the field investigated. Further trials were made on a boiler model in which the riser was electrically heated to produce an evaporation up to 80 lb. per sq. ft. per hr. The velocity of circulation was measured. The results showed the dependence of velocity of circulation on pressure and heat input. Heat transfer rates varied from 1200 to 2600 B.t.u. per sq. ft. per hr. per deg. fahr. for the heat conveyed from tube walls to the steam-water mixture.

CIRCULATION in boilers is known to be caused by the difference in specific densities between the steam and water mixture in highly heated riser tubes and the water in the downcomer tubes. Consider the simplest form of boiler having but one riser and one downcomer between drums; if the downcomer is unheated, steaming will not have begun at the lower end of the riser because the entering water temperature, being equivalent to that of saturation at the steam pressure existing at the water surface in the steam drum, must first be raised to the saturation temperature equivalent to the drum pressure plus the added pressure caused by the hydrostatic head of the column of mixture in the riser. At a certain point such temperature is reached and steaming begins. The tube now fills up with a steam and water mixture of which the mean specific weight diminishes toward the top.

For a given circulating velocity, the difference in weights of the water column in the downcomer and of the mixture column in the riser, is exactly equal to the sum of the resistances of the circuit. These include resistances due to flow in the tubes and the entrance losses of the risers and downcomers, which last losses are recovered at the exit of the tubes to a very small extent or not at all. To these must be added the pressure loss dP for speeding up the steam-water mixture in the risers. This loss is proportional to the square of the weight of water G, entering the sectional tube area f in a unit of time, and the increase in the specific volume of from V_1 for the entering water to V_2 for the leaving mixture.

$$dP = \frac{1}{g}\left(\frac{G}{f}\right)^2 (V_2 - V_1) \qquad (1)$$

If, for the present, the resistance due to flow be taken from hydrodynamic experiments, then the only difficulty in calculating the water velocity remains in determining the specific weight and thereby the steam content of the mixture in the riser.

Knowing the heat absorption along all points of the riser, the steam added to the water at such points is found. If it is assumed that the steam bubbles have no relative velocity with respect to the water, but are simply carried along with it, then a theory of circulation may be established in a relatively simple manner and the circulation calculated for given conditions. Such a theory provides a picture of the circumstances in a broad way, but is insufficient for more exacting investigations because it neglects two actual conditions.

Self-Evaporation

First the so-called self-evaporation is not considered. If the water enters the bottom of a riser tube at saturation temperature equivalent to the pressure in the bottom drum, then as it rises it enters regions of lower hydrostatic pressures and lower saturation temperatures. Water will therefore evaporate in an unheated riser and it is possible to reverse the water flow as shown by an experiment wherein the water in a downcomer was heated just sufficiently so that it rose in temperature from that of saturation in the upper drum to that of saturation in the lower drum without generating any steam and then rose in the unheated riser with considerable steam generation. Steam is generated in such a riser just as it is when drawn down from an accumulator; it is not generated at the wall but within the body of the fluid. Fig. 1 shows how the extent of self-evaporation may be calculated from a temperature-entropy diagram, or from the steam tables. Point A represents the beginning of evaporation, point B saturation at the water level. Self-evaporation occurs along line AC without any added heat, the percentage of evaporation $dx = BC/BD$ may be calculated from the steam tables for a given pressure drop dP with the aid of equation

$$dx = \frac{1}{s'' - s'}\frac{ds'}{dP} \qquad (2)$$

Calculations show that the influence of self-evaporation is considerable and may materially exceed the steam generation due to heat transmission through the walls of a riser at very low and intermediate pressures. Circulation is aided by self-evaporation and its consideration adds to the complexity of the theory, but does not offer any basic difficulties.

The "Running Ahead" of the Steam Bubbles

Further, the running ahead of the steam bubbles with respect to the water in a riser is neglected in the above theory. This is likewise not permissible, because the speed of the steam bubbles is of the same magnitude and often greater than the

* Translated from an article published in *Wärmewirtschaft*, January, 1933.

circulating speed of the water. Because of the running ahead of the steam bubbles, the steam content of the mixture is diminished and thereby the lifting power, so that circulating velocity decreases with an increase in the running ahead of the steam bubbles.

Both of the omissions in the above theory are therefore of considerable weight; they may, however, equalize each other in particular cases, in that they influence the circulation in opposite directions.

The running ahead of the steam bubbles may be likewise considered in the theory of circulation but its magnitude can only be established by experiments. It is of interest to consider comparatively the rising velocities of single steam or air bubbles in water. Observations of bubbles rising through water by Hoefer (in air lifts) showed that such a comparison is not feasible, because the higher relative velocities of the bubbles in a mixture of air and water within an air lift tube are much greater than rising velocities of single bubbles in a large tube.

The departure is due to the distinctively different character of performances in the two cases. A single, not too small, bubble within a large body of water assumes a spherical form when rising and moves relatively slowly and uniformly upward. However, if you blow steam or air into the bottom end of a not too cramped glass tube, the bubbles rise in quite irregular fashion up through a wildly turbulent mixture. Only in tubes of about 2 cm. and less may bubbles be observed which have a bullet-like form, which almost fill the entire cross-section of the tube and which rise uniformly while retaining their form. What happens varies therefore with the tube diameter and, consequently, conclusions should not be drawn from experiments made on small diameter tubes and applied to determining the rising velocities of bubbles in boiler tubes of usual measurements, as has been attempted.

If a single bubble in a large body of water rises much slower than many bubbles in a not too cramped tube, then the rising velocity becomes in the main dependent upon bubble content and thereby upon the specific volume of the mixture. The shape of the bubbles and condition of flow are also materially influenced by the viscosity and the surface tension. Because both of these values decrease rapidly with rising temperature of water, it is to be expected that the condition of flow will vary with the saturated pressure.

"Running-ahead" Velocities at Atmospheric Pressures

In order to obtain a survey of conditions, experiments were conducted at atmospheric pressures in an apparatus as shown in Fig. 2. Tube *a* is filled with water and is provided with an electrical heater *b* made of chrome-nickel, supplied with alternating current in order to avoid dissociation. The steam bubbles rise and form a steam-water mixture whose composition throughout the length of the tube is nearly constant. The steam is led away downward between tube *a* and an enveloping tube, *c*, thereby preventing radiation from tube *a* to the atmosphere. An adjustable measuring tube *d* dips into the mixture from above, having holes *e* near its lower end. Air under a slight pressure is admitted to this tube so that small single bubbles leave the bottom holes and rise with the steam bubbles. The pressure is measured by a liquid manometer, not shown, and represents the hydrostatic pressure of the column of mixture at the holes. Evaporation is replenished by an automatic supply from below so that the weight of the mixture in the tube remains constant during the experiment and may be observed by means of manometer *f*.

Experiments were conducted with this preliminary rig on tubes of 1.1, 1.7 and 3.23 in. dia. and of lengths up to 9.85 ft. at atmospheric pressure. For the purpose of an example, the results of trials on a 3.23-in. tube are here given in Fig. 4. Ordinates show the height of the holes of the measuring tube *e* above the electric heater, abscissas the corresponding pressures of the injected air. Readings are shown in small circles and are connected by lines. The dotted line shows the pressure dis-

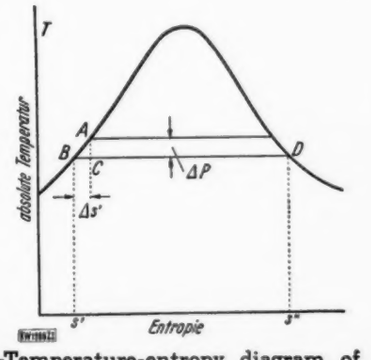


Fig. 1—Temperature-entropy diagram of steam for calculating the self-evaporation.

ΔP, pressure drop; AC, line of self-evaporation; BC/BD, proportion of steam; $\Delta s'$, drop in entropy

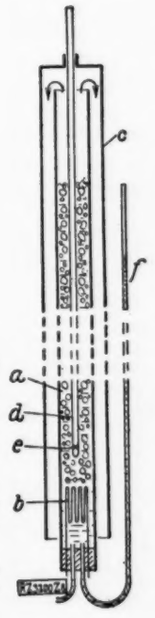


Fig. 2—Apparatus for measuring the relative velocity of the steam bubbles in a steam-water mixture at atmospheric pressure.

a, tube filled with water; *b*, electric heater; *c*, jacket tube; *d*, pressure-measuring tube adjustable from above; *e*, holes in side of tube *d*; *f*, water-column manometer

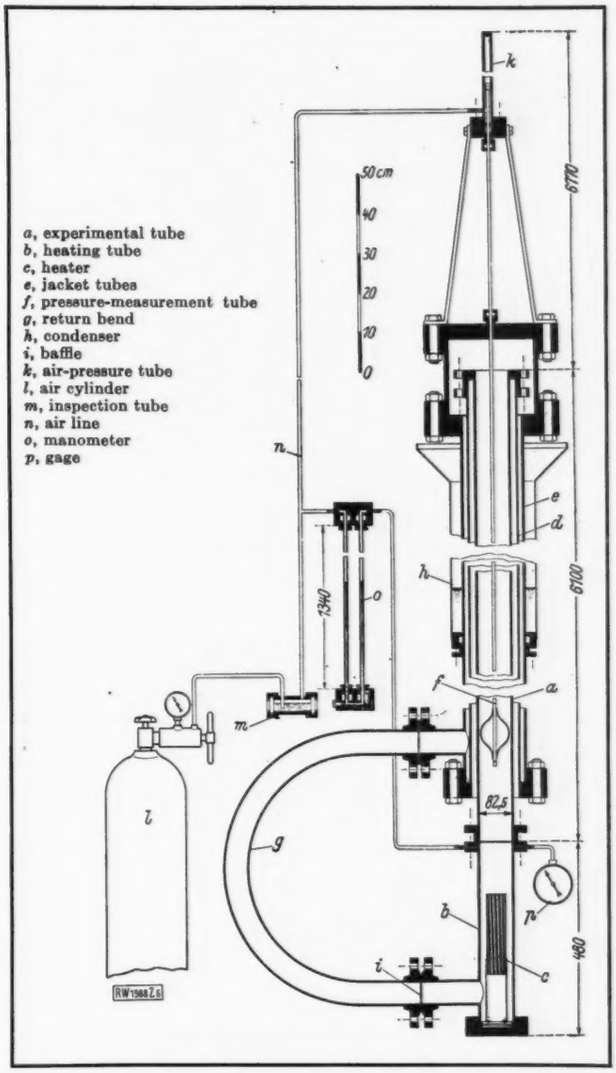


Fig. 3—Apparatus for measuring the relative velocity of steam in steam-water mixtures in tubes for pressures up to 570 lb.

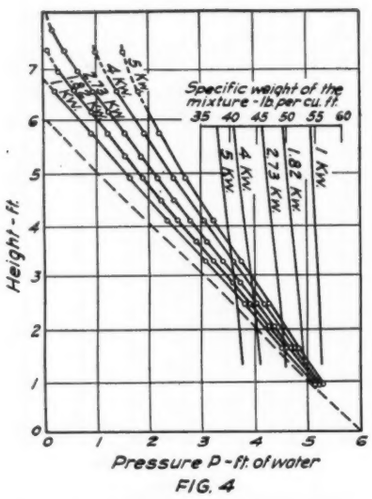


FIG. 4

Fig. 4—Pressures and specific weights of steam-water mixtures in a tube of 3.23 in. dia. for different heat inputs.

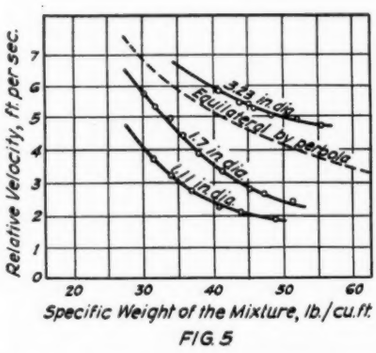


FIG. 5

Fig. 5—Dependency of the relative velocity W_{dr} of the steam bubbles on the specific weight of the steam-water mixture within tubes of different diameters.

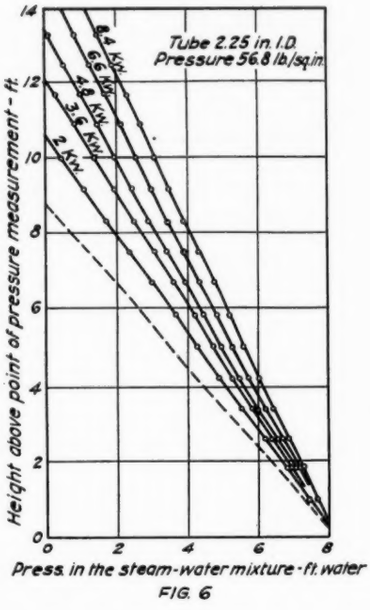


FIG. 6

Fig. 6—Pressure variation along a column of steam-water mixture within a tube of 2.25 in. i.d. at 5.7-lb. gage and heat inputs of from 2 to 8.4 kw.

tribution within a steam-free water column. The various, nearly straight lines, representing pressure variations, were taken with heat inputs of from 1 to 5 kw. The measurements were easily taken in spite of the turbulence of the mixture. Only those at the top of the tube, where the lines are shown dotted, were unsteady because the surface fluctuated violently.

The specific weights of the mixture are obtained from the deviations of the pressure lines and are also recorded in Fig. 4 in relation to the height. The specific weights slightly decrease upwardly which may be accounted for by the expansion of the bubbles. At higher pressures, the influence of the variation in pressure as the bubbles rise through the mixture becomes relatively less so that, as will be shown later, the pressure lines become nearly straight and the specific weight becomes constant throughout the entire height of the column.

The percentage by volume of steam in the mixture may be obtained from the measured mean specific weight of the mixture and the known specific weights of water and steam. Knowing these and the quantity of steam, as determined from the heat input of the electrical heater, it is possible to find the velocity of the steam or, stated differently, the mean rising velocity of the steam bubbles. The results of these preliminary experiments made on tubes of three different diameters at atmospheric pressure are shown in Fig. 5, wherein the relative speed W_{dr} of the steam is shown with respect to the mixture in terms of specific weight of the mixture. It is apparent that the relative speed increases nearly in hyperbolic relation to the decrease in density of the mixture.

Experimental Apparatus for Higher Pressures

Based on the experiments conducted at atmospheric pressure, an apparatus was designed for higher pressures, of which Fig. 3 is illustrative. An experimental tube *a* of 20 ft. length and of 3.25, 2.72 or 2.25 in. i.d. is heated by electrical means *c*. The space between tubes *a* and *d* is insulated with aluminum foil. Tube *e* is in communication with *a*, the condensate flowing back through insulated bend *g*. The upper part of *e* is cooled by condenser tube *h*, the amount of condensation being regulated by the water level in *h*. All exposed parts are insulated.

Steam produced by heater *c* rises through tube *a*, forming a column of mixture which may rise to 19.7 ft. in height. Steam rising above the mixture condenses above and within tube *e*, returning through bend *g*, through baffle *i* (which stops possible pendulum-like oscillations), to tube *a*. Pressure measuring tube *f* may be moved up and down, and has small outlet holes at its lower end through which a small amount of air is

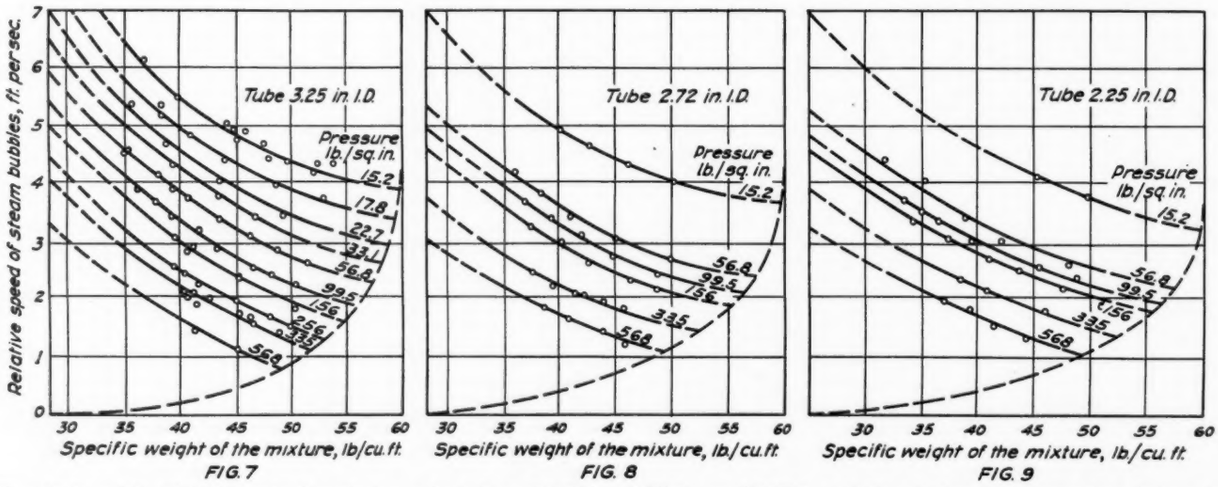


FIG. 7 FIG. 8 FIG. 9

Figs. 7, 8 and 9—Relative velocity of steam in tubes of 3.25 in., 2.72 in. and 2.25 in. i.d. for various pressures in relation to the specific weight of the mixture.

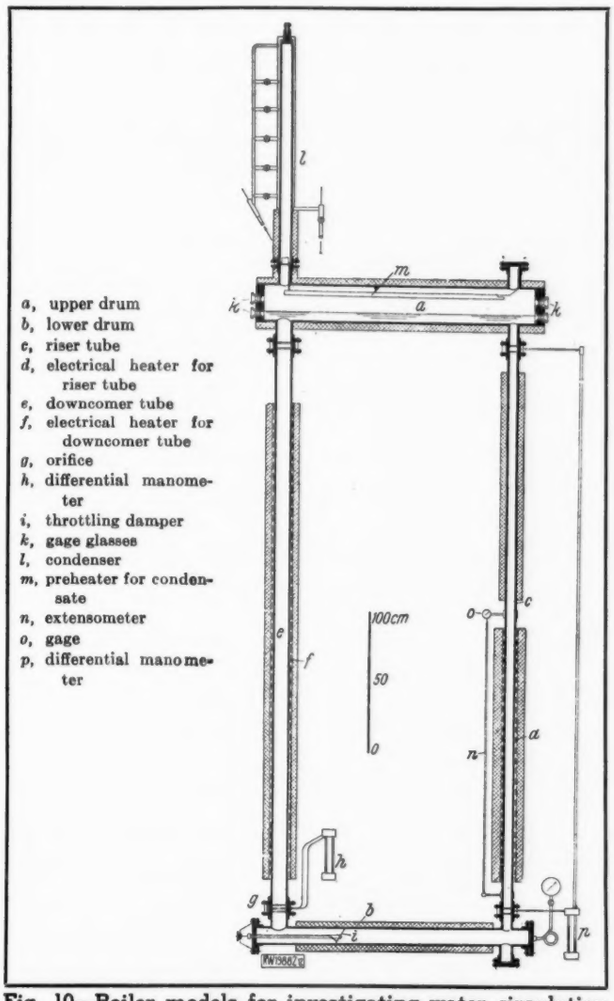


Fig. 10—Boiler models for investigating water circulation for pressures up to 570 lb.

permitted to bubble into tube *a*, thereby giving a pressure measurement at that point. To check these measurements, which may be doubtful at higher pressures, a tetrabrom-ethane (sp. wt. 3.0 kg. per liter) manometer *o* was used for comparison with the measurements of tube *f* at this point. At this point is also connected the control manometer *p*, for measuring the pressure in tube *a*.

Test Results

Fig. 6 shows the pressure gradient along the column of steam-water mixture with a 2.25 in. i.d. tube, 57 lb. overpressure and heat transfer rates of from 2 to 8.4 kw. The pressure relation is a straight line, the mixture therefore has a constant specific weight for its entire height. For comparison, the dashed line shows the pressure for a steam-free column of water at saturation temperature. From these results are found the relative velocities of the steam bubbles with respect to the mixture, for tubes of different diameters and pressures up to 570 lb.

Figs. 7 to 9 show the relative velocity of the steam in tubes of 3.25, 2.72 and 2.25 in. dia. for various pressures, in relation to the specific weight of the mixture. The speeds increase with decreasing specific weight of the mixture, i.e., with increased bubble content, but decrease considerably with increase in pressure. Performances at atmospheric pressures are therefore of no use for high pressure. The differences in speeds for the different tube diameters is small, so that they are independent of tube diameter for the usual limits of from 1.97–3.55 in. Note the decided reduction in the relative speed of the steam bubbles with rising pressure. At high pressures, therefore, the circulation is retarded less, because of the running ahead of the steam bubbles, than at low pressures.

Tests on a Boiler Model

To fit the experiment to a practical design, an apparatus was built adapting more nearly the conditions in a boiler. (See Fig. 10.) It is suitable for pressures up to 570 lb. Its height is 13.1 ft. Riser *c* is provided with electric radiant heating elements *d* for a distance of 6.56 ft. which can develop a steaming capacity of 41 lb. per sq. ft. per hr. for a 2.25 in. tube and 82 lb. per sq. ft. per hr. for a 1.18 in. tube. Downcomer *e* is mildly heated by heater *f*. The entire boiler is insulated. Orifice *g* measures the flow of water by means of manometer *h*. Temperature measurements are made at various places. Resistance may be increased by damper *i*. Windows *k* provide inspection of the water level. Condenser 1 condenses the steam, the amount being measured by the temperatures of the cooling water. Condensate is led through the steam space in a sloping gutter *m* in order to avoid under cooling. To obtain the mean tube wall temperature, extensometer *n* measures the elongation at gage *o*. To measure the circulation resistance, manometer *p* is connected top and bottom.

Downcomers were heated only enough to balance losses. Water enters into the bottom end of the riser at the saturation temperature of the surface pressure. Steaming begins accordingly at some distance above the entrance, particularly at low pressures.

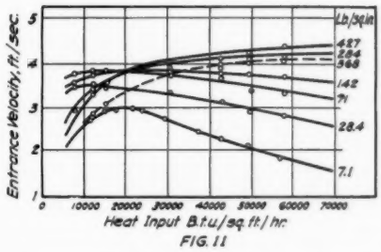


FIG. 11

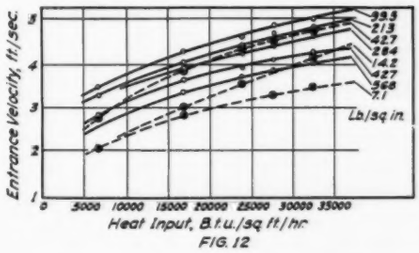


FIG. 12

Figs. 11 and 12—Results of measurements on the boiler model.

Showing the dependency of the water-circulating velocity W_o at the entrance into the riser tube on the heat input to the tube surface for various working pressures. Fig. 11 for a 1.18-in. i.d. tube. Fig. 12 for a 2.26-in. i.d. tube

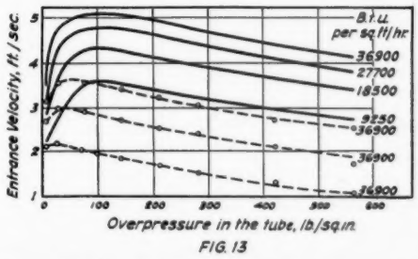


FIG. 13

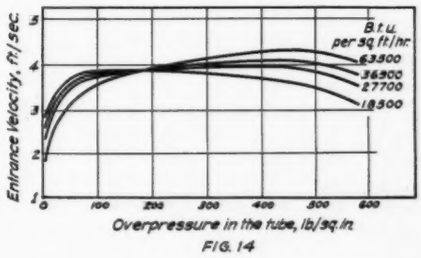


FIG. 14

Figs. 13 and 14—Water-circulating velocities W_o at the entrance into the riser tube in relation to the working pressure for various heat inputs to the tube surface.

Fig. 13 for a 2.25-in. i.d. tube. Fig. 14 for a 1.18-in. i.d. tube
——— without throttling
– – – – – with different degrees of throttling

Test Results

Fig. 11 shows the relation of entrance velocity of the water W_o into the riser and the heat input for various pressures. At low pressures in the 1.18-in. i.d. tube, the velocities reach a peak as the amount of heat input increases and then decreases, which is in accord with theory. The drop is due to increased flow resistance. At high pressures, the peaks lie beyond the experimental range, which also are not reached in practice. Fig. 12 shows similar results for a 2.26-in. i.d. tube.

Fig. 13 shows the same experiments for a 2.26-in. tube, converted to pressure as abscissa and heat input as parameter. The rapid decrease in velocity at low pressures is due to the volume increase and the consequent rise of flow resistance as well as the rise of the point at which steaming begins within the tube. The dashed lines were the results of throttling the circulation.

In Fig. 14 are shown similar results with a 1.18-in. i.d. tube. At high pressures, the velocity increases with increase in heat input as would be expected, but at low pressures the reverse is true. An intermediate range exists, where the lines cross, where neither steam pressure nor heat added affects the velocity materially.

Further analysis indicates that apparently the frictional resistances of the steam-water mixture are considerably higher than measurements made with pure water. This surprising disclosure may be explained by the greater turbulence caused by the rising bubbles which result in a higher friction. Further investigations will be made.

A.S.A. Establishes New Sub-Committee on Application of Scientific Classification of Coal

A new subcommittee on the Application of Scientific Classification of Coal has been appointed by W. H. Fulweiler, chairman of the Technical Committee on Use Classification, a subdivision of the Sectional Committee on Classification of Coals (M20) under the procedure of the American Standards Association. The new subcommittee will act as a correlating committee to harmonize the scientific classification of coal as prepared by the Technical Committee on Scientific Classification with the practical use classification of coal as worked out by the Technical Committee on Use Classification.

The membership of the new subcommittee is as follows: T. W. Harris, Jr., division purchasing agent, E. I. du Pont de Nemours and Company, Wilmington, Delaware, *chairman;* Gilbert Francklyn, fuel agent, Consolidated Gas Company of New York, New York, *secretary;* S. B. Flagg, fuel engineer, Phoenix Engineering Corporation, New York; J. B. Morrow, preparation manager, Pittsburgh Coal Company, Pittsburgh; Malcolm MacFarlane, Bird Coal Company, New York; R. E. Gilmore, superintendent, Fuel Research Laboratories, Department of Mines, Ottawa, Ontario.

The American Society for Testing Materials is sponsor for the project on Classification of Coals.

The Homestead Valve Manufacturing Co., Coraopolis, Pa., recently appointed the following companies as exclusive representatives covering the Philadelphia and New England States territories respectively for the sale of the HYPRESSURE JENNY, a vapor spray machine used for automotive, industrial, aeronautical and building cleaning: Reeves-McCormick, Inc., 5317 N. Second St., Philadelphia, Pa.; Clark-Wilcox Company, 790 Albany St., Boston, Mass.

Boiler Manufacturing and Affiliated Industries Submit Industrial Recovery Code

As this issue goes to press, word is received that the American Boiler Manufacturers Association and Affiliated Industries has submitted its industrial recovery code to Washington and that the code has been surveyed by the Code Analysis Division and is now being returned to the Association for possible revision. It is expected that the National Recovery Administration will shortly appoint a day for a hearing.

Work on the development of the code was begun at the annual meeting of the American Boiler Manufacturers Association which was held at Sky Top Lodge, Pa., during the week of June 5, concurrently with the annual meetings of the Stoker Manufacturers Association and the Pulverized Fuel Equipment Manufacturers Association. At the Boiler Manufacturers' meeting it was voted to extend the scope of membership to admit manufacturers of stokers and pulverized fuel equipment in order that manufacturers closely associated with boiler manufacturing might be properly considered in the preparation of a code that would be representative of the entire industry. It was also voted to change the name of the association to "American Boiler Manufacturers Association and Affiliated Industries."

Following the adoption of this resolution by the Boiler Manufacturers, all members of the Pulverized Fuel Equipment Manufacturers Association voted to disband their association and become affiliated with the Boiler Manufacturers. A majority of the large stoker manufacturers, previously identified with the Stoker Manufacturers Association, took similar action.

The American Boiler Manufacturers Association and Affiliated Industries then appointed a committee to prepare a code. The committee appointed was designated as the A.B.M.A. Committee of Industrial Recovery, and the following members of the Association were selected to serve on this committee:

Owsley Brown, Chairman
Springfield Boiler Company

A. C. Weigel, Vice Chairman
Combustion Engineering Corporatic

Starr H. Barnum
The Bigelow Company

H. H. Clemens
Erie City Iron Works

Walter F. Keenan, Jr.
Foster Wheeler Corporation

R. B. Mildon
Westinghouse Elec. & Mfg. Co. (Stoker Division

A. G. Pratt
The Babcock & Wilcox Company

A. W. Strong
Strong-Scott Manufacturing Company

Charles Tudor
Tudor Boiler Manufacturing Company

The Committee, in accordance with the authority delegated to it by the Association, appointed James D. Andrew as manager of the association, in responsible charge of the work of preparing the code, and Henry E. Aldrich as full-time secretary. Both Mr. Andrew and Mr. Aldrich are engineers who have had extensive executive experience and are well known to the industry. The Committee's headquarters have been established at 15 Park Row, New York.

Design Features of the Port Washington Power Plant*

By G. G. POST[1]

This paper, presented here in somewhat abridged form, is an analytical discussion of the major decisions reached in the design of the new Port Washington power station. The factors affecting design questions, selection of equipment, steam cycle and temperature and other important problems are outlined sufficiently to make apparent the reasons for the decisions made. The economic studies made in connection with some of the principal problems are included in tabular form.

THE Port Washington generating station of The Milwaukee Electric Railway and Light Company, now under construction, is located on the west shore of Lake Michigan at East Port Washington, Wisconsin, 28 miles north of Milwaukee. The station's initial capacity will be 80,000 kw. (one unit) with a possible ultimate capacity of 400,000 kw. (five units). The outstanding feature will be its unit design, that is, there will be a single boiler for each single turbine generator and also one set of transformers, one 132-kv. transmission line, and one set of auxiliaries for each unit.

Fundamentally, Port Washington's design is based on that of the Lakeside plant except that such advancements are incorporated as are justified by operating experience and improvements in the power plant art. The principal advancement, aside from the unit arrangement which has been mentioned, is the adoption of 825 fahr. temperature for both throttle and reheat.

Selection of Site

Load growth made it apparent in 1928 that generating capacity would have to be added to the Wisconsin-Michigan system of the North American Company in order to maintain the proper relation between system capacity, peak demand, and reserve capacity. With by far the major portion of the system's generating capacity concentrated at one point, Lakeside, south of Milwaukee, it was deemed advisable not to put "all the eggs into one basket" by further expansion of Lakeside, whose capacity had reached 310,800 kw. but to locate a new plant at a point north of Milwaukee which would permit feeding energy into the Milwaukee district from two almost diametrically opposite and widely separated sources.

In the case of power plants in the Milwaukee area, water-borne coal has a distinct advantage over all-rail coal from the same field in the eastern district. This is caused by the decided and abrupt railroad rate increase on coal in passing through the Chicago district. In fact, the increase is so large that even midwestern coal (Indiana and Illinois), which must of necessity pass through Chicago, cannot compete with the eastern coal when the latter is shipped by water. The comparisons given assume the various coals on an equal B.t.u. basis. This point is mentioned to bring out the importance of selecting a site where coal can be received by water.

The selection of a site, therefore, resolved itself into a search for one which would most nearly fulfill the following requirements:

1. Be north of the Milwaukee metropolitan area better to insure continuity of service. (Lakeside is south.)
2. Be located as close to the load center as practicable.
3. Be adjacent to Lake Michigan where the condensing water supply is ample and cold.
4. Be at a location where harbor facilities for lake boats have been established or could be provided at reasonable cost.
5. Be at a location to which large industries might be attracted so that these could be served with energy directly from the station bus bars.
6. Be located so that connections to railroad lines (preferably the company's own) could readily be made.

Port Washington was the only place that met satisfactorily all of these requirements. In addition, if in the future combination of coal prices and freight rates should become such as to give rail-borne coal an advantage over water-borne coal, the change to rail-borne coal could be made at Port Washington without any difficulty whatever.

Although Lakeside burns water-borne coal it has not a dock of its own. Its coal is received over the docks of Milwaukee coal companies and from there hauled to the plant by rail. Port Washington, on the other hand, will have a coal dock which will eliminate the intervening rail haul with its attendant costs. The effect of this will be to lower its fuel cost about $2.59 per hundred million B.t.u. below that of the Lakeside plant.

Determination of Size

In determining the size of the plant and of the units, the possibility of supplying industrial concerns that might wish to locate in the vicinity of the plant was an important factor. Because of its harbor, dock, and railroad facilities, Port Washington offers to new industries advantages far superior to those that can be found anywhere else in the vicinity of Milwaukee. Because of this it was felt that it would not be beyond reason to contemplate the possibility of industrial development in the vicinity of the plant to the extent of about 150,000 kw.

The load growth on the system in 1928, when Port Washington was originally planned, amounted to 37,000 kw. over the year previous, with prospective increases for 1929 and 1930 of 40,000 kw. each. For the latter two years provisions were

* *Presented at the summer convention of the A.I.E.E., Chicago, Illinois, June 26–30, 1933.*

[1] Vice President in Charge of Power, The Milwaukee Elec. Rwy. and Light Co., Milwaukee, Wisconsin.

made for adding 75,000 kw. to Lakeside's capacity. Increases of 40,000 kw. each for two years succeeding 1930 were not then unreasonable.

The fact that Lakeside's last two additions were of 75,000 kw. capacity each, that normal load had been increasing at the rate of nearly 40,000 kw. per year, and that there was a possibility of a large industrial load, in addition to the normal growth, prompted the decision to install 80,000 kw. initially at the new station.

Mercury-Steam Cycle Consideration

The possibility of large industrial plants locating in close proximity to the power station, some of which might require large amounts of process steam in addition to their electrical demands, suggested that serious consideration be given the mercury-steam cycle. For a given process steam demand, the mercury cycle can generate over twice as much by-product electrical energy as can a straight steam cycle, or conversely, the net heat consumption in B.t.u. per switchboard kw. hr. would be considerably less with the mercury cycle than with a straight steam cycle if the kw.-hr. outputs were the same. On the basis of straight condensing plants of equal capacity (100,000 kw.) it was found that the mercury-steam cycle in order to equal the 1200-lb steam cycle in total annual costs would have to be operated at an annual load factor on the plant of at least 65 per cent. At lower load factors, the 1200-lb. steam cycle showed a saving. For the particular project under consideration, the 1200-lb. steam cycle showed a saving in investment costs of $18.74 per kilowatt while the mercury cycle showed a gain of 2550 B.t.u. per kw. hr. in station heat consumption. With coal at $3.80 per ton and fixed charges taken at 13 per cent, the total annual costs (including fixed charges) would be the same at 63½ per cent load factor, while with coal at $3.60 per ton they would be the same at 67 per cent load factor. In these calculations allowances have been made for the smaller amount of auxiliary power and the lower capacity of condensing water and coal handling and preparation facilities required by the mercury cycle. It is obvious that with lower coal costs the money saving due to saving a certain quantity of coal becomes less and the installation of the more expensive mercury equipment becomes more difficult to justify.

It was concluded that the mercury cycle should not be adopted for the initial section of the plant for the following reasons.

1. Because of the small net savings, if any, which the mercury cycle could show over the 1200-lb. cycle,
2. Because some of the untried portions of the fundamental parts in the mercury equipment might cause an outage when the capacity could not be spared for any appreciable time, especially not for correcting developmental defects, and
3. Because the mercury cycle could be installed in succeed-

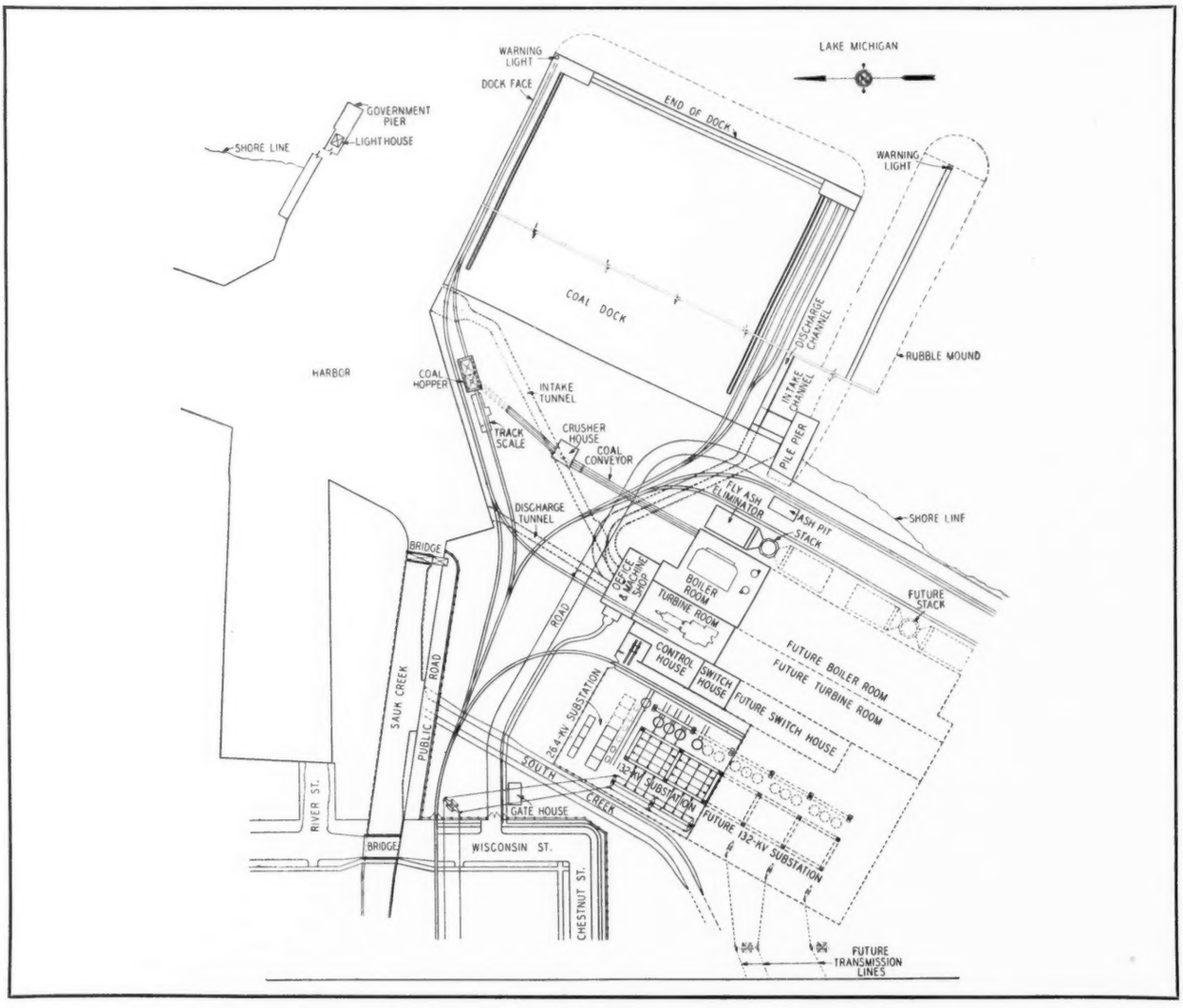


Fig. 1—General plan of present Port Washington plant and future extensions.

The plant is situated conveniently for condensing water, coal handling and transmission line facilities. Its unit design permits flexibility in adopting different forms of generating equipment for future extensions.

ing units very readily, should these experimental matters prove successful.

At the time of making the mercury-steam study, indications of future price trends both of fuel and construction materials were taken into consideration. Recent trends have been along the lines assumed and have not altered the conclusions reached.

Selection of 1200-Lb. Steam Cycle

As has been stated, the design for the Port Washington plant has as its underlying basis the design and operating experiences of the Lakeside plant. Lakeside's first 1300-lb. boiler was placed in operation in October 1926. In October 1929, its second high-pressure boiler went into service. By the time that a decision on the pressure for the Port Washington plant had to be made, 3½ years of operating experience had been had with the Lakeside equipment. The availability factor for the last 2 of these 3½ years on high-pressure boilers was 84.3 per cent and 88.5 per cent, respectively. (Incidentally, it might be interesting to record at this point that during 1932 the availability for the 4 high-pressure boilers at Lakeside averaged 93.7 per cent.) A careful analysis of the operating statistics for 1929, the last full year before making decisions for Port Washington, showed that Lakeside's high-pressure system had in that year effected an actual net saving of $58,965 over straight 300-lb. equipment of the latest and the most modern design. The actual fuel saving resulting from 14.12 per cent less coal burned amounted to $89,365 against which was made an offset of $30,400 for annual fixed charges on the larger investment; maintenance costs being the same for 1200 lb. as for 300 lb. (See Table I.)

TABLE I—COMPARISON OF ACTUAL 1200-LB. GENERATION WITH 300-LB. GENERATION
LAKESIDE—1929

Economy		
1.	Station generation, million kw. hr.	993.9
2.	Station output, million kw. hr.	948.7
3.	Generation by 1200-lb. cycle, million kw. hr.	236.0
4.	Per cent of generation by 1200-lb. cycle	23.8
5.	Overall station heat consumption at Lakeside, B.t.u. per kw. hr. net	14,882
6.	Heat consumption of an all 300-lb. plant, B.t.u. per kw. hr. net	15,400
7.	Heat consumption of an all 1200-lb. plant, B.t.u. per kw. hr. net	13,225
8.	Heat saving on 1200-lb. generation, B.t.u. per kw. hr. net	2,175
9.	Per cent saving of 1200 lb. over a new 300-lb. plant = item 8 divided by item 6	14.12
10.	Total 100 million B.t.u. saved = item 3 times item 8 divided by 100,000,000	5,133
11.	Cost of fuel per 100 million B.t.u.	$17.41
12.	Total saving for 1929, 1200 lb. over 300 lb.	$ 89,365
Investments		
13.	Greater investment cost of 1200-lb. equipment over 300 lb. (per unit)	$200,000*
14.	Greater annual fixed charges at 13 per cent	$ 30,400
Net Saving		
15.	Net saving for 1929, 1200-lb. cycle over new 300-lb. cycle	$ 58,965

Actual operating statistics showed that Lakeside's 1200-lb. cycle had saved 14.12 per cent in coal over that which would have been burned had 300-lb. equipment been installed. Maintenance costs were no higher and, except for slightly higher fixed charges, the fuel savings indicate the net savings.

These economy and reliability figures definitely established 1200-lb. pressure as being far superior to 300 lb., 300-lb. pressure being used in this comparison because the existing equipment in the plant, before the installation of the 1200-lb. equipment, was built for it. But in order to exhaust all possible claims for intermediate pressures, a comparison was made between 600 lb. and 1200 lb. The results, shown in Table II, indicated that the 1200-lb. cycle would save $36,754 annually over the 600-lb. cycle in the initial installation at Port Washington, after deductions had been made for fixed charges on the greater investment required.

Consideration of the possibilities of the Benson cycle showed that it held no inducements at this time. Efficiency gains due to pressures above 1200 lb. were found to be slight because of rapidly increasing feed pumping costs and steadily decreasing energy gains.

The savings shown in Tables I and II, together with satisfactory overall operating experiences at Lakeside, were sufficient to warrant the adoption of 1200 lb. for Port Washington.

TABLE II—COMPARISON OF 1200-LB. GENERATION WITH 600-LB. GENERATION
(Reheating to Same Temperature for Both Pressures)
ESTIMATED FOR PORT WASHINGTON

Economy		
1.	Estimated annual generation for initial installation 80,000 kw. at 60 per cent annual load factor, million kw. hr.	421
2.	Saving in heat consumption by 1200-lb. cycle over 600 lb. (average all loads), B.t.u. per kw. hr.	856
3.	Annual B.t.u. saving in favor of 1200-lb. 100 million B.t.u. per year	3,610
4.	Cost of fuel per 100 million B.t.u.	$14.82
5.	Total annual fuel saving, 1200 lb. over 600 lb.	$ 53,500
Investments		
6.	Greater investment for 1200-lb. boiler room equipment...	$147,168
7.	Greater investment for 1200-lb. turbine room	$ 19,300
8.	Lesser investment for 1200-lb. turbine room equipment..	$ 20,000
9.	Lesser investment for 1200-lb. station tunnels, circulating water system, and coal handling system	$ 17,650
10.	Net greater investment for 1200-lb. installation	$128,818
11.	Annual fixed charges on greater 1200-lb. investment at 13 per cent	$ 16,746
Net Saving		
12.	Net annual saving of 1200-lb. installation over 600-lb. installation of 80,000-kw. capacity	$ 36,754

In comparing the economies of 1200-lb. generation with 600 lb. a considerable saving in fuel was found. This, together with the unexcelled reliability record of Lakeside's 1200-lb. equipment decided the issue in favor of 1200 lb.

Selection of 850 Fahr. (Maximum) Steam Temperature

Lakeside has a reputation for being a pioneering station in economically sound ventures. Thanks to a liberal company policy, marked by keen foresight, every opportunity has been given to improve the art of producing and distributing electrical energy. In planning Port Washington this same policy was continued. It was believed that progress should be made and that some improvements over Lakeside were possible. Among those considered was the possibility of going to a higher steam temperature. Superheater manufacturers, valve, pipe, and also turbine makers were consulted. All expressed their willingness to cooperate and subsequently quoted prices on equipment necessary not only to produce 825 fahr. at the turbine throttle and reheat point, but to maintain it continuously: 850 fahr. was specified as the maximum. The increase of 75 fahr. in actual operating temperature (Lakeside's is 750 fahr.)

TABLE III—COMPARISON OF 825 FAHR. AND 750 FAHR. TEMPERATURE AT BOTH THROTTLE AND REHEAT—ESTIMATED FOR PORT WASHINGTON

Economy		
1.	Estimated annual generation for initial installation, 80,000 kw. at 60 per cent annual load factor, million kw. hr.	421
2.	Saving in heat consumption, 825 deg. over 750 deg., B.t.u. per sw. bd. kw. hr.	300
3.	Annual B.t.u. saving, 825 deg. over 750 deg., 100 million B.t.u.	1,263
4.	Cost of fuel per 100 million B.t.u.	$14.82
5.	Total annual fuel saving, 825 deg. over 750 deg.	$ 18,720
Investments		
6.	Investment saving of 825 deg. due to lower heat consumption, %	2.5
7.	Unit investment to which heat saving applies, $ per kw.	47.30
8.	Total investment saving of 825 deg. = $47.30 times 80,000 times 2.5 per cent	$ 94,600
9.	Total investment saving assuming 75 per cent of total saved	$ 71,000
10.	Additional investment saving in two steam drums, due to lesser storage required	$ 5,670
11.	Additional investment saving due to deferring replacing last rows of blades because of lesser moisture in exhaust	$ 10,920
12.	Total investment saving, 825 deg. over 750 deg.	$ 87,590
13.	Greater investment cost of 825-deg. turbine	$ 89,000
14.	Greater investment cost of 825-deg. valves and fittings..	$ 8,000
15.	Greater investment cost of 825-deg. superheater and reheater	$ 18,760
16.	Total greater investment cost, 825 deg. over 750 deg...	$115,760
17.	Net greater investment cost, 825 deg. over 750 deg. (item 16 minus item 12)	$ 28,170
Net Saving		
18.	Annual fuel saving, 825 deg. over 750 deg.	$ 18,720
19.	Annual fixed charges on greater investment at 13 per cent	$ 3,650
20.	Net annual saving, 825 deg. over 750 deg.	$ 15,070

An increase in operating temperature to 825 fahr. from 750 fahr. for both throttle and reheat showed a 2.5 per cent improvement in station performance. When the saving was capitalized on the basis of reducing equipment costs in the boiler room, it offset the increased cost of the turbine, valves and fittings and showed a substantial net saving for the higher temperature.

* Second unit started in commercial operation November 1, 1929.

brings the total steam temperature up to the point where ordinary steels cannot be used in the turbine. Alloys require greater investment particularly in large turbines where they had not been previously applied to the extent that they had been in steam superheating equipment and in valves. The net greater cost of 850 fahr. equipment totaled $28,170 in investment. With fixed charges taken at 13 per cent, the annual rate amounted to $3650. The fuel saving on the other hand amounted to $18,720 per year, resulting from a 2.5 per cent better station heat consumption rate. The net saving was, therefore, calculated to be $15,070 per year. The greater investment resulted from a more expensive turbine, greater cost of valves and fittings, and greater cost of superheaters and reheaters. These greater costs were offset by investment savings in boiler plant equipment due to the smaller amount of steam required, less water storage required in steam drums, and by deferred expenditure for replacing the last row of turbine blades due to less moisture in the exhaust steam. (See Table III.)

A higher steam temperature than 825 fahr. at the turbine throttle with no reheat was considered purely experimental because it involved untried alloys. Creep in metals is hardly a consideration at 825 fahr., but at 1000 fahr. or thereabouts, it is extremely important. A throttle temperature of 825 fahr. with reheat at the same temperature is a reliable, non-base-load combination, one that is made particularly attractive through the application of radiant superheating and reheating surfaces in the same furnace.

Lakeside's operating experiences with reheat are positive proof that variable loads are easily and safely carried. Reheat introduces minimum complications into the cycle.

One Turbine, One Generator, and One Boiler

A previous study had shown that one large turbine generator would save $7.15 per kw. over two half-size units in investment costs (turbine generators, foundations, turbine room building, electrical equipment, and switch house) and about $25,000 per year in operating costs due to a better rate of heat consumption. These savings were considered sufficient to warrant the installation of an 80,000-kw. unit rather than two 40,000-kw. units. Incidentally, an 80,000-kw. machine would match almost exactly the 90,000-kva. transmission lines which had been adopted for the Milwaukee district.[2]

Most of the original 1200-lb. installations in this country consist of 1200-lb. non-condensing turbines superimposed on existing 300-lb. stations. In such installations, of course, new full capacity 1200-lb. boilers were required but the turbines were of comparatively small generating capacity. The economy of such an installation, due to having to maintain a practically constant pressure at the exhaust of the high pressure turbine for all loads, drops off rapidly in going from full load to partial load. Multiple-valve admission to the high-pressure turbine has been used as a partial means of overcoming this difficulty, but the process effects a saving in the high-pressure turbine only, whereas the largest part of the loss occurs at the exhaust of this turbine.

If the exhaust pressure is permitted to vary according to load through the use of so-called compound operation, savings of considerable magnitude can be made. Such operation naturally would have to be followed in a station which had boilers generating steam at but one pressure. The high-pressure turbine could, however, still remain segregated from the low through the adoption of a cross-compound machine. There then would be two separate turbines each with its own generator, a combination which has the advantage of keeping the low-pressure turbine in service when trouble is encountered in the high-pressure turbine. Should the low pressure section be forced from service at any time, the entire unit would be down and because of this fact a reserve equal to the capacity of the whole unit must be kept available at all times. The ability to operate the low-pressure section at times of high-pressure turbine outage, therefore, loses much of its significance. Besides, the reserve capacity in most cases can be operated at an economy very close to that of the low-pressure section alone. The advantages of tandem-compounding on the other hand are such as to win approval; they are, net investment savings of $1.12 per kw. resulting from (1) a lower cost of the turbo-generator itself, (2) fewer electrical connections because of having only one generator, (3) less building volume, and (4) a credit for a smaller turbine room crane because of a narrower turbine room.

Many of the arguments presented against the cross-compound unit apply to the steeple-compound unit also, although the economic advantage of the tandem over the steeple is not as great as it is over the cross compound. Inconvenience in operation and maintenance were also factors in deciding against the steeple-compound unit.

After having established the size and type of the turbine to be installed, the next consideration was the number, size, and type of boilers. Detailed comparisons were made on the installation of two boilers of small size (345,000 lb. per hour capacity) and of one boiler of large size (690,000 lb. per hour capacity).

One boiler was selected rather than two, because:

(1) An investment saving of approximately $250,000 could be made.

(2) The operation would be simpler due to not having to apportion the exhaust steam from the high-pressure section of the turbine to each of the two reheaters.

(3) The presence of an 80,000-kw. turbine generator on the system would require 80,000-kw. reserve in any event. Therefore, no additional losses in capacity would occur due to boiler outage.

At Lakeside, three-drum, bent-tube type boilers with comparatively large low-heat-release furnaces had unprecedented reliability records. Certainly records of this nature could not be ignored in making selections for the Port Washington boilers. This fact notwithstanding, all arguments for the single-drum straight-tube boiler and high-heat release furnace were obtained and carefully weighed. Prices were secured and tentative layouts prepared so that an unbiased opinion as to their merits might be formed.

TABLE IV—COMPARISON OF BOILER DESIGNS FOR PORT WASHINGTON—INITIAL INSTALLATION

		Bent-Tube Boiler Low-Heat Release Furnace	Straight-Tube Boiler High-Heat Release Furnace
1.	Total investments in boiler, furnace, superheater, reheater, economizer, air-heater feeders, burners, and milling equipment*	$937,137	$838,805
2.	Greater investment of bent-tube boiler	98,332	
3.	Greater annual fixed charges at 13 per cent	12,783	
4.	Increased operating costs		
	a. Greater pressure drop in superheater		$ 156
	b. Greater pressure drop in reheater		1,920
	c. Loss of heat in molten ash		1,780
	d. Lower overall boiler efficiency		6,370
	e. Poorer availability		3,900
	f. Lower reheat temperature		2,720
	g. Greater furnace maintenance cost		5,700
	h. Total greater operating costs		$ 22,546
5.	Net annual saving of bent-tube boiler with low-heat release furnace	$ 9,763	

The bent-tube boiler with a low-heat release furnace not only will produce an annual saving of $9763 but will also permit the use of radiant superheat and reheat surfaces within the furnace, and afford other operating advantages.

* Building not included because costs would be identical.

Exponents of the straight-tube boiler design with its complementary equipment maintained that with it a better proportioning of all of the heat reclaiming surfaces could be secured together with a lower overall investment cost. The use of less of the comparatively high cost boiler surface and more of the less expensive economizer surface formed the basis for their arguments. They also maintained that less building volume would be needed. Contrary to expectations, the latter was not

[2] See paper on "The 60-Cycle Primary Transmission System of the Milwaukee Electric Railway and Light Company and Associated Companies in Wisconsin and Upper Michigan," by C. D. Brown and E. W. Hatz, A.I.E.E. paper presented at the Great Lakes District Meeting at Milwaukee, Wisconsin, March 16, 1932.

found to be true for Port Washington conditions, principally because of a 10-ft. higher building which would be required. It was true, however, that a small saving in investment was shown with the straight-tube boiler layout over that of the bent-tube type but this saving was more than offset by operating losses. Table IV summarizes these gains and losses. Then, too, high-pressure economizers (1600 lb.) which are an essential part of the straight-tube boiler layout were considered a potential source of trouble. As explained later, economizers were eliminated entirely from the Port Washington design.

It was concluded finally to adopt the bent-tube type boiler fired from one side only with a low-heat-release, hopper-bottom furnace beneath it. Besides the economic gains and the possibility of eliminating economizers, the following additional reasons influenced its selection:

(1) About 50 per cent more water storage space is available which is very important when only a few minutes total storage is available.

(2) Tubes being nearly vertical permit rapid water circulation which eliminates wide variations in drum-water levels throughout the load range.

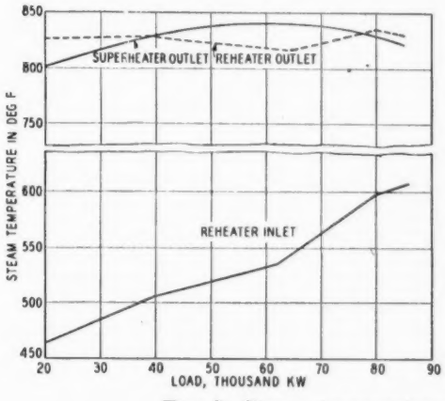
(3) Dry steam is obtained since the rear drum acts as a dry drum, it having little steam released from the water it contains.

(4) Water wall connections can easily be made because of accessibility of the drums.

(5) Suspended solids in the boiler water are removed effectively in the lower drum.

Furnace

The slag-tap furnace, which was given some consideration, is a high-heat-release furnace of relatively small size because the temperature in the furnace must be kept sufficiently high to maintain the ash in a molten state. The small size and high temperature preclude the use of radiant superheaters and reheaters. The latter are desirable because their inherent characteristics are such as to give automatically the most economical operating conditions at all loads. Superheaters and reheaters



Uniform steam outlet temperatures such as these, from both the combination radiant and convection super-heater and the radiant reheater, over a load range from full to quarter will tend to produce high overall plant efficiency

Fig. 2—Steam temperatures.

of the all-convection type give decidedly variable steam outlet temperatures with variations in load on the boiler necessitating desuperheating at the higher loads. This was considered objectionable because of the general unreliability of the desuperheating process. No desuperheater is required with the radiant surfaces in the Port Washington station design. On the other hand, large furnaces with a low rate of heat release (15,000 B.t.u. per cu. ft. per hr., maximum) are conducive to low maintenance costs and high availability. With steel walls consisting of steam- and water-cooled surfaces on all 6 sides, there can be no wall erosion. Radiant superheater and reheater surfaces for side and rear walls and water tubes for the front wall and the ash screen were the final answer to the furnace problem after all advantages and disadvantages of other combinations had been carefully balanced.

Radiant Superheater and Reheater

Selection of radiant heat-absorbing surfaces for superheater and reheater rather than all-convection surfaces was prompted by economic considerations as well as the adaptability of these surfaces to the low-heat release furnace mentioned in the previous paragraph. More uniform steam temperatures over wide load ranges can be obtained automatically and thus the overall station economy can be improved. This is particularly true at low loads when all other factors in the system are working toward poorer economy. By virtue of the higher superheat the turbine efficiency is maintained higher than it would otherwise be at the lower loads.

The superheater selected has a radiant section and a convection section. The steam will pass first through the former and then the latter. With this combination the steam temperature to the turbine throttle will vary only from 830 fahr. at full load to 802 at quarter load. The reheater on the other hand is radiant entirely and its outlet temperature will vary from 834 at full load to 827 at quarter load.

Air Heater and Economizer Considerations

Economizer and air heater surfaces—all waste heat reclaiming surfaces for that matter—are closely related to the type of cycle adopted for the station. In the case of Port Washington, a tentative cycle was decided upon at the time of placing the turbine contract. This called for the use of extraction heaters at 5 points. A comparison between 4 extraction heaters plus an economizer-air heater combination, and 5 extraction heaters plus an air heater only, indicated that a net annual saving of $7429 could be made through the use of the latter. The major portion of this saving is effected by the 1.3 per cent better heat rate of the turbine due to the fifth heater. Although the addition of an economizer would reduce the flue gas temperature 25 fahr. and thus effect some improvement in boiler efficiency, the fixed charges on the greater investment for the economizer and piping (after taking credit for the smaller air heater) and the maintenance costs on the economizer would more than offset this gain. Five-stage heating with an air-heater but with no economizer was therefore decided upon.

TABLE V—COMPARISON BETWEEN 4 EXTRACTION HEATERS PLUS ECONOMIZER-AIR HEATER COMBINATION AND 5 EXTRACTION HEATERS PLUS AIR HEATER ONLY

Four Extraction Heaters Plus Air Heater Only Is Used as the Basis for This Comparison

ESTIMATED FOR PORT WASHINGTON

		Gain	Loss
Four-Stage Heating and Economizer			
1.	Saving due to lowering of flue gas by 25 fahr.	$4520	
2.	Maintenance cost on economizer		$2000
3.	Pumping cost for pressure drop through economizer		120
4.	Fixed charges on greater investment cost for economizer and piping after deducting credit for smaller air heater, $35,800 at 13 per cent		4654
5.	Total costs	$4520	$6774
6.	Net annual loss for economizer		2254
Five-Stage Heating			
7.	Better heat consumption rate due to fifty-stage heaters—112 B.t.u. per kw. hr.	$6995	
8.	Maintenance cost on fifth-stage heaters		400
9.	Pumping cost per pressure drop through heaters		120
10.	Fixed charges on investment in fifth-stage heaters, also necessary piping, $10,015 at 13 per cent		1300
11.	Total costs	$6995	$1820
12.	Net annual gain for fifth-stage extraction heaters	5175	
Net Comparison			
13.	Net gain due to fifth-stage heaters	$5175	
14.	Net loss due to economizer	2254	
15.	Net annual difference in favor of fifth-stage heaters	$7429	

Economizers ordinarily are thought of as equipment used to enhance power plant operating efficiency. This tabulation shows that extraction heaters do this more effectively, and with far less need for worry about operating difficulties under the higher pressures encountered.

Bin-and-Feeder vs. Unit System

In determining the method of firing to be adopted, a thorough investigation was made into the adaptability of the unit system and of the bin-and-feeder system to the contemplated plant layout. The results showed that the boiler efficiency obtain-

able with the unit system was about equal to that of the bin-and-feeder system with no gain for either on such items as carbon loss, uniform grinding, etc. There were, however, inherent advantages of the bin-and-feeder system which influence total station economy rather than only boiler efficiency and it was these which decided the matter in its favor. The most outstanding of these advantages are:

(1) Greater reliability. With the unit system any outage of a mill for any reason will cause a reduction in capacity of the boiler or complete outage of the boiler. Whenever a reduction in load occurs, it must be picked up by some standby or less efficient station, and a loss of 0.1 per cent in economy might result.

(2) Flexibility. The low rating limitation of the unit mill is absent entirely from the bin system. This is particularly important at times of starting when low furnace temperatures are desired to prevent damaging superheater tubes.

(3) Mill drying with flue gas can be used in the storage system to advantage, while on the other hand it cannot be used efficiently in the unit system. Venting flue gases back into the furnace is not conducive to efficient combustion and to the maintaining of proper flame control. With flue gas drying in a storage mill 6 per cent of the total flue gas discharges to the stacks at a temperature 200 fahr. lower than the usual exit temperature. In addition, air heater performance is improved due to the greater mean temperature difference and the lesser heat absorption in the air heater. After the flue-gas mill drying system has been charged with the small coal vent loss, it shows a net gain of 0.5 per cent over using hot air and venting to the furnace.

(4) Coal feed can be regulated more closely with the storage system resulting in the maintenance of high average CO_2 and fine control of excess air. With radiant superheaters and reheaters this is important. Coal feed variations of 10 per cent as is common with the unit system without hand adjustment can cause a 50 deg. variation in reheat temperature and 0.6 per cent decrease in station economy.

(5) Coal feed control at Lakeside where the storage system is used has been found to be so regular that boiler pressure can be regulated to within 5 lb. of a standard. With the unit system, the pressure variations might be on the order of 50 lb. The difference of 45 lb. in pressure at the turbine could cause 0.6 per cent difference in economy.

(6) When using air drying with unit mills the heated air to the mill must be tempered with room air. This reduces the amount of air to be taken through the air heater and reduces the boiler efficiency about 0.3 per cent below that of a storage system boiler where flue gas drying is used.

(7) Automatic combustion control is much more positive on a storage fired boiler than on a unit-fired one. With the latter, difficulties are encountered in coordinating the mill speed, primary air volume, and sizing of the pulverized coal particles with the requirements of the boiler. Lower overall efficiencies will result.

These advantages, totaling 2.1 per cent in station economy, can be credited to the storage system. Investment costs were found to be 74c. per kilowatt lower for the unit system. Labor, maintenance, and power were slightly in favor of the unit system. An important point in favor of the storage system is that most of its motors can be shut down at the time of the station peak. The unit system on the other hand requires peak electrical demand for auxiliaries coincident with the peak station demand and to provide the same margin in capacity an equivalent in generating capacity must be installed at the same station or elsewhere.

Another important advantage of the storage system is the safety to personnel and equipment occasioned through the use of flue gas for mill drying. A 12 per cent volume of CO_2 (an inert gas) is maintained in the mill system and collectors, so that danger of fire or of an explosion from smoldering coal is lessened materially.

TABLE VI—COMPARISON OF STORAGE SYSTEM AND UNIT SYSTEM OF PULVERIZED FUEL FIRING—ESTIMATED FOR PORT WASHINGTON

Economy		
1.	Estimated annual generation for initial installation, 80,000 kw. at 60 per cent annual load factor, million kw. hr.	421
2.	Saving in heat consumption, storage over unit, %	2.1
3.	B.t.u. saving, storage over unit, B.t.u. per kw. hr.	252
4.	Annual B.t.u. saving, storage over unit, 100 million per year	1,061
5.	Cost of fuel per 100 million B.t.u.	$14.82
6.	Total annual fuel saving, storage over unit	$15,750
Labor, Maintenance and Power		
7.	Greater cost of labor (1 extra man) storage over unit	$ 2,400
8.	Greater cost of maintenance, storage over unit	$ 950
9.	Lesser cost of power, storage over unit	$ 575
10.	Net greater operating costs, storage over unit	$ 2,775
Investments		
11.	Greater investment cost in mills, feeders, burners, motors, starters, duct work, foundations, air compressors, fuel bins, etc., storage over unit	$59,112
12.	Greater annual fixed charges at 13 per cent, storage over unit	$ 7,685
Station Peak Capacity		
13.	Greater kw. demand of unit system motors at time of station peak	592
14.	Value of 592-kw. station capacity at $75 per kw.	$44,400
15.	Lesser annual fixed charges on station capacity, storage over unit	$ 5,772
Net Saving		
16.	Net annual saving, storage system over unit system (item 6 minus item 10 minus item 12 plus item 15) =	$11,062

The battle of storage vs. unit system of pulverized fuel firing was waged for many weeks in The Milwaukee Electric Railway and Light Company's engineering department before the storage system was awarded the decision. Its merits include not only an annual saving of $11,062, but greater reliability and flexibility, as well as safety, due to the possibility of using flue gas mill drying with it.

The analysis, of which Table VI is a summary, showed the bin-and-feeder system to effect a net annual saving of $11,062 and this, together with certain operating advantages, formed the basis for its adoption.

Extraction Heaters and Feed Pumps

After having determined the number of extraction heaters to be used in the heat cycle, a very important decision had to be made in regard to the location of the boiler feed pumps in the cycle. The high pressure boiler feed pumps at Lakeside, although they had been operating continuously for over four years and had never been the cause of 1200-lb. equipment outage, had demanded considerable attention and were creating maintenance costs which were considered too high. Their operation as a whole was rather delicate. An investigation showed the cause of the difficulties to be fluctuations in feedwater temperatures which set up uneven expansion and contraction in the various component parts of the pumps causing clearance variations, packing leaks, etc. The maximum feedwater temperature delivered to the Lakeside 1600-lb. pressure pumps is 360 fahr. while it might go down to 300 fahr. or slightly below at light loads. The pumps at Port Washington, if they are placed on the discharge side of the extraction heaters, would be required to handle water to as high as 432 fahr. temperature at full load and as low as 290 fahr. at quarter load, a condition much more severe than that at Lakeside. Should they be located after the second heater, however, and made to discharge through the heaters at the remaining 3 extraction points, the temperature of the water entering the pumps could be held constant at 200 fahr. The manufacturers of the feed pumps were in hearty approval of the suggestion that the lower temperature be used in spite of the relatively low delivery pressure to the suction of the pumps, and promptly quoted on pumps with efficiency guarantees somewhat improved over those at Lakeside. This improvement in efficiency is incidental to the improved reliability of the pumps and to the 12 per cent saving in pumping energy occasioned by the lower specific volume of 200 fahr. feedwater compared with that of 400 fahr. feedwater. The somewhat higher cost for the high-pressure extraction heaters over the lower pressure type was not nearly enough to offset the advantages mentioned.

Two sets of high-pressure extraction heaters will be used, one on each of the feed lines to the boiler. Each feed line will have

a separate high-pressure pump with a spare pump so connected that it can be substituted in either line. Two feed lines to the boiler will be used because better parallel operation of centrifugal feed pumps can be obtained when discharging through heaters and piping before pressures are equalized. Then, too, it was found economical to use two sets of heaters because bypasses around the heaters with their expensive fittings could be eliminated.

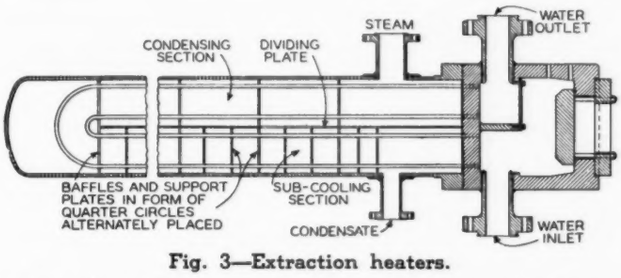


Fig. 3—Extraction heaters.

Built for 1600 lb. water pressure, the extraction heaters presented an operating problem until this design with its elimination of bolted heads with gaskets and stay-bolts was adopted

Interesting design details entailed in the construction of the high-pressure extraction heaters are worthy of mention because they have heretofore never been attempted. It is common knowledge that bolted heads with gaskets and stay-bolts are a serious problem in the use of high-pressure heaters. These have been entirely eliminated through the adoption of a head made from a solid forging bored out and supplied with an internal head cover, similar to a boiler manhole plate design.

Steel tubes with *U*-bends have been decided upon because experience at Lakeside has proved them to be more reliable than brass tubes and they cost less. Corrosion of the tubes can be prevented entirely by complete de-aeration which is essential in any event in a 1200-lb. pressure plant.

Flash losses between the high-pressure heaters will be eliminated by cooling the drains in the lower sections of the heaters before cascading them into the next lower heaters. Separate drain pumps on individual high pressure heaters would be impractical because of having to pump against 1300-lb. boiler pressure. Calculations show an improvement of about $^3/_4$ per cent in plant economy through the elimination of flash losses.

Conclusion

The author wishes to emphasize that the comparisons presented in this paper and the conclusions reached apply to Port Washington conditions. Under other conditions, decisions might have been different.

It is hoped that the information presented in this paper will convey a general impression of certain trends in power plant design as interpreted by the engineers of The Milwaukee Electric Railway and Light Company.

The author wishes to acknowledge the valuable assistance in the preparation of this paper of F. L. Dornbrook, Chief Engineer of Power Plants, William E. Gundlach, Chief Electrical Engineer, C. F. John, Assistant to Vice President, and others of the engineering staff of The Milwaukee Electric Railway and Light Company.

Equipment Details of Port Washington Power Plant*

Boiler

Three-drum, bent tube type—heating surface, 44,100 sq. ft.—maximum steam output, 690,000 lb. per hr.—maximum steam pressure, 1390 lb. gage—average operating pressure, 1320 lb. gage—feedwater temperature, 430 fahr.... *Combustion Engineering Corporation.*

Superheaters

Convection type, located behind first bank of boiler tubes—heating surface, 8700 sq. ft.... *Foster Wheeler Corporation.* Radiant type, located in side walls of furnace—heating surface, 1464 sq. ft.... *Foster Wheeler Corporation.* Steam temperature, 825 fahr.—deg. of superheat, 245 fahr.

Reheater

Radiant type, located in rear wall of furnace—heating surface, 1740 sq. ft.—steam temperature to reheater, 605 fahr.—steam temperature from reheater, 830 fahr.... *Foster Wheeler Corporation.*

Air heaters

Two—vertical plate counterflow—area, 60,500 sq. ft. each.... *Combustion Engineering Corporation.*

Furnace

Volume above water screen, 58,000 cu. ft.—volume, total, 73,000 cu. ft.—heating surface, water screen and waterwall, 7710 sq. ft.—maximum coal burning rate, 66,000 lb. per hr.—side walls, steam-cooled by radiant superheater—rear wall, steam cooled by reheater—front wall, water-cooled by fin tubes—furnace width, 55 ft.—furnace height, average below arch, 26 ft. 6 in.—furnace depth, 24 ft. $3^1/_2$ in.... *Combustion Engineering Corporation.*

Coal burning equipment

Ten feeders, type R—capacity, 6600 lb. per hr. each.... *Combustion Engineering Corporation.* Twenty burners, Lopulco vertical forced-draft type.... *Combustion Engineering Corporation.*

Stack

Concrete—300 ft. above base—22 ft. 0 in. I.D. at base—17 ft. 10 in. I.D. at top.

Induced draft fans

Two—steel-plate type—capacity, 185,000 c.f.m. each—11.5 in. S.P. at 370 fahr.—motor driven.... *B. F. Sturtevant Company.*

Forced draft fans

Two—turbovane type—capacity, 112,500 c.f.m. each—10 in. S.P. at 120 fahr.—motor driven.... *B. F. Sturtevant Company.*

Primary air fans

Two—turbovane type—capacity, 23,500 c.f.m. each—15 in. S.P. at 630 fahr.—motor driven.... *B. F. Sturtevant Company.*

Hot gas fans

Two—steel-plate type—capacity, 14,100 c.f.m. each—7.5 in. S.P. at 550 fahr.—motor driven.... *B. F. Sturtevant Company.*

Mill vent fans

Two—steel-plate type—capacity, 10,350 c.f.m. each—6.5 in. S.P. at 135 fahr.—motor driven.... *B. F. Sturtevant Company.*

Evaporators

Two—low-pressure, bent-tube type.... *Griscom Russell Company.*

Extraction heaters

Two—low-pressure and six high-pressure, bent-tube type—5 points of extraction.... *Griscom Russell Company.*

Boiler feed pumps

Three—capacity, 350,000 g.p.m. each at 1500 lb. discharge pressure—seven stages—two motor driven—one turbine driven.

House service pumps

Three—capacity, 500 g.p.m. each at 200 lb.—1000 g.p.m. each at 200 lb.—1500 g.p.m. each at 100 lb.—two motor driven—one steam driven.... *Allis-Chalmers Mfg. Company.*

Raw coal handling equipment

Coal grizzly—capacity, 150 tons per hr.... *Robins Conveying Belt Company.* Hammer crusher—capacity, 150 tons per hr.... *Pennsylvania Crusher Company.* Belt Conveyors—conveyor "A"—track hopper to coal crusher—capacity, 265 tons per hr.—width, 48 in.—rise, 60 ft.—speed, 140 ft. per min. Conveyor "B"—coal crusher to boiler room—capacity, 280 tons per hr.—width, 36 in.—rise, 90 ft.—speed, 270 ft. per min. Conveyor "C"—above raw coal bunker—capacity, 300 tons per hr.—width, 36 in.—rise, 2 ft.—speed, 300 ft. per min.

Coal pulverizing equipment

Mills—two Raymond roller—capacity, 20 tons per hr.—motor

* Not included in original paper. Published here by courtesy of the author.

driven.....*Combustion Engineering Corporation.* These mills are arranged for mill drying with flue gas.

Fuel pumps

Two—capacity, 25 tons per hr. each.....*Combustion Engineering Corporation.*

Coal bunker

Raw coal bunker—capacity, 1100 tons—pulverized coal bunker—capacity, 290 tons.

Ash conveyor

164 ft. of 24-in. trench sluice.

Main generating unit

Capacity, 80,000 kw.—reaction type blading—H.P. section, 65 rows of blading—2 L.P. sections, 8 rows of blading each—throttle pressure, 1230 lb. gage—throttle temperature, 825 fahr.—exhaust pressure, 29 in. hg.—5 stages of extraction.... *Allis-Chalmers Mfg. Company.* Generator—capacity, 80,000 kw.—1800 r.p.m.—power factor, 85 per cent—voltage, 22,000 (a.c. 60 cycle)—main exciter, 300 kw.—pilot exciter, 5 kw.

Condenser

Surface type—single pass—52,500 sq. ft. tube surface.... *Allis-Chalmers Mfg. Company.*

Circulating pumps

Two—horizontal split casing type—capacity, one operating 73,000 g.p.m.—two operating 110,000 g.p.m.—motor driven.... *Allis-Chalmers Mfg. Company.*

Hotwell pumps

Two—capacity, 1000 g.p.m.—head pressure, 200 ft. of H_2O—motor driven.... *Allis-Chalmers Mfg. Company.*

Steam jet air pumps

Two—Croll-Reynolds twinevactor type.... *Allis-Chalmers Mfg. Company.*

Circulating water screen

Two—traveling type—motor driven.... *Chain Belt Company.*

Principal electrical features

Generator and main bus voltage, 22,000 volts—indoor, vertical phase isolation switching.

Worthington and Gamon Consolidate Meter Interests

The Worthington Pump and Machinery Corporation and the Gamon Meter Company have consolidated their operations in the manufacture and sale of meters through the newly organized Worthington-Gamon Meter Company. Sales headquarters for the company have been established at Harrison, N. J. All manufacturing operations, however, will be concentrated in the Gamon plant in Newark, N. J.

Officials of the new company are as follows: E. T. Fishwick, *President;* G. H. Gleeson, *Vice President in Charge of Sales;* J. A. Bonnet, *Secretary;* R. R. Anderson, *Works Manager.* These officials will be recognized as having been drawn entirely from the Worthington and Gamon organizations.

Complete lines of meters, as previously built by Worthington and Gamon for hot and cold water, beverages, chemicals, oil and grease, in disk, turbine, compound and piston types, will be continued.

The Riley Stoker Corporation announces the removal of its Pittsburgh office from 1419 Farmers Bank Building, to 1420 Investment Building, 239 Fourth Avenue. Mr. Van A. Reed, Jr., and Mr. L. C. Frohrieb are in charge of the new office.

A.S.M.E. Nominates Officers for 1934

Nominations for officers of The American Society of Mechanical Engineers for 1934 were announced at a recent meeting of the Nominating Committee held at Chicago, Ill., during the Semi-Annual Meeting. Election will be held by letter ballot of the entire membership, closing on September 26, 1933.

The nominees as presented by the Regular Nominating Committee of the Society are:

President—Paul Doty, Chairman of the Board, Minnesota State Board of Registration, St. Paul, Minn.

Vice Presidents—H. L. Doolittle, Designing Engineer, Southern California Edison Company, Los Angeles, California; William L. Batt, President, SKF Industries, Inc., 40 East 34th Street, New York, N. Y.; Ely C. Hutchinson, President, Edge Moor Iron Company, Edge Moor, Delaware; Elliott H. Whitlock, Cleveland, Ohio (Formerly Research Professor, Stevens Institute of Technology, Hoboken, N. J.).

Managers—James M. Todd, Consulting Engineer, New Orleans, La.; Ernest L. Ohle, Professor, Mechanical Engineering, Washington University, St. Louis, Mo.; James A. Hall, Professor, Mechanical Engineering, Brown University, Providence, R. I.

The Chapman Valve Manufacturing Company, Indian Orchard, Mass., and the Automatic Cone Valve Company of Mattoon, Ill., have made an agreement whereby the Chapman Valve Manufacturing Company has been given the exclusive right and license to the manufacture and sale of all products heretofore manufactured by the Automatic Cone Company.

The entire personnel of the Automatic Cone Valve Company has been retained by the Chapman Valve Manufacturing Company. Mr. David D. Goldberg, previously General Manager of the Automatic Cone Valve Company, will have direct charge of all Cone Valve sales work and engineering design at the home offices of the Chapman Valve Manufacturing Company, Indian Orchard, Mass.

The Worthington Pump and Machinery Corporation, Chicago, announce the appointment of the Kroeschell Engineering Company, 2306 North Knox Avenue, Chicago, as authorized dealer in the Chicago area for Worthington Refrigeration Compressors of all types and sizes, and Worthington Vacuum Refrigeration Units as applied to both air conditioning and direct refrigeration.

Regulator Companies Change Name

The Mason Regulator Co., Boston, manufacturers of automatic regulating and control equipment, and the Neilan Co. Ltd., Los Angeles (subsidiary of the Mason Co.), have consolidated. The name of the new company is the Mason-Neilan Regulator Co.

The engineering, manufacturing and sales departments of the two individual companies have been combined at 1190 Adams Street, Boston, Mass. Mr. F. Kenneth Morrison, former Sales Manager of the Mason Regulator Co., will continue in this same position for the consolidated company. Douglas H. Annin, Chief Engineer of the Neilan Co. for several years, will serve in a similar capacity in the new Mason-Neilan Regulator Company.

This union brings under the Mason-Neilan trademark a complete line of automatic pressure regulating valves, liquid level controllers, as well as compensated instruments for controlling pressures, temperatures, rates-of-flow and combustion.

Progress in the Removal of Sulphur Compounds from Waste Gases[1]

By H. F. JOHNSTONE[2]
Urbana, Illinois

This paper discusses some of the results obtained in a cooperative investigation that is being made at the Engineering Experiment Station of the University of Illinois. The purpose is to determine the effectiveness and the mechanical and economic feasibility of various chemical processes in the removal of sulphur compounds from waste gases. The investigators hope to find a method that will not only render the gases free of dust and obnoxious sulphur fumes but that will also result in the recovery of a by-product of some value. . . . The results indicate that the possibility of economically washing large quantities of gases, such as those from central station boilers, with untreated water is very remote. A comprehensive study of the catalytic oxidation method for removing sulphur dioxide has been made. Work has been started on the development of a regenerative system for recovering sulphur dioxide using alkaline reagents.

THE problem of atmospheric pollution is a specific branch of the science of air conditioning, to which considerable attention has been given in the last few years. In the burning of coal the contribution to pollution in the form of smoke and dust has been fully realized and to a large extent has been eliminated by what might be called economically profitable methods. On the other hand, the harmful effect of the gaseous products of combustion, especially the sulphur compounds, was only fully recognized when two events focused public attention on this source of pollution. The first of these was the legal decision given in connection with the Barton Station at Manchester, England, holding the power company responsible for damage to vegetation and crops caused by sulphur compounds in the stack gases. The startling catastrophe in the Meuse Valley in France which followed soon after this, in 1930, and which was officially attributed to the concentration of sulphur fumes due to peculiar atmospheric conditions, created a firm foundation for public opinion on the question. In this country utilization of low grade fuels, both in the form of coal and refinery wastes, has also aggravated the question.

This paper will discuss a part of the results obtained in a cooperative investigation at the Engineering Experiment Station of the University of Illinois with the Utilities Research Commission, Inc. Here a study is being made of various chemical processes that might increase the mechanical and economical feasibility of the sulphur removal. It is the hope not only that it will be possible to render the gases entirely free of dust and obnoxious sulphur fumes, but also that a by-product of some value will be obtained.

While the sulphur acids are present to a very small extent in the gases, their chemical activity is great, and the possibility of finding a solution to the problem will be enhanced by the use of chemical engineering methods related to gas absorption. We consider this an opportune time for this discussion for, perhaps as a result of too great enthusiasm, various claims are being made by manufacturers of gas washers that exceed the bounds of probability and are contrary to the experience both of our work and of other reported results.

The ultimate goal to be reached in this problem is the removal of the sulphur compounds with expenditure of the least amount of capital and energy. If a washing process is to be used, this means building the smallest contact device and pumping the smallest volume of liquid. Thus we have an intensity and capacity factor with which to deal. It will be obvious, first, that there will be an economic balance between these two and that one may be increased in order more beneficially to decrease the other. Also, since power plants are not in the business of purifying gases nor of producing sulphur chemicals, the process must not appreciably interfere with the operation of the boilers, such as by greatly increasing draft losses, etc.

Theory of Gas Washing

In separating a component from a gaseous solution the solubility of the particular gas determines the magnitude of both the quantity of liquid and the contact required. Obviously, the more soluble the gas is, the less liquid will be required for its removal. Furthermore, the greater the difference between the saturation point and the quantity of gas already dissolved in the liquid, the faster will the gas dissolve. If the gas is only slightly soluble this difference cannot be great and the rate of absorption is slow. Of as great importance, however, the solubility of the gas determines the type of washer suitable for the absorption. The explanation of this is found in the two-film theory as discussed in the papers of Lewis and his co-workers at Massachusetts Institute of Technology (*1*).*

It is considered that there are two resistances to the passage of the gas into solution. One of these, the gas film, consists of a layer of indefinite thickness above the interface, in which the molecules are in relatively slow motion as compared with those in the main body of gas. Passage of the gas being absorbed takes place to a large extent only by simple diffusion rather than by convection. Similarly, beneath the interface, there is a relatively stagnant liquid film through which the dissolved gas at the interface must diffuse to reach the main body of the liquid. The conditions may be considered as wholly analogous to heat transfer from a hot gas through a thin metal wall to a liquid. These ideas are graphically illustrated in Fig. 1.

[1] Presented by the Fuels Division of the A.S.M.E. at the semi-annual meeting of the Society, Chicago, June 25–July 1, 1933. Published by permission of the Director of the University of Illinois Engineering Experiment Station.

[2] Special Research Assistant Professor of Chemical Engineering, Engineering Experiment Station, University of Illinois.

* Numbers in parentheses refer to references at end of article.

The solubility of the gas determines the relative importance of these two films. At the interface the dissolved gas is considered in complete equilibrium with the undissolved gas. In the case of a highly soluble gas, this means that the diffusion gradient through the liquid film, i.e., the difference in concentration between the two sides, is always large, except when the liquid is near saturation. Since the rate of transfer through the liquid film is proportional to this gradient, the diffusion will be rapid, or, in other words, the resistance of the liquid film will be small. On the other hand, diffusion through the gas film depends on the gradient, or concentration difference, between the sides of this film. Especially when the concentration of the absorbable gas in the main body of the gas is small, will the diffusion be slow and the resistance be relatively large. For absorbing very soluble gases, therefore, we consider that the gas film controls the rate of absorption and the liquid film plays only a small part.

For slightly soluble gases the relation is just reversed. Here the concentration gradient through the liquid film cannot be large, since it is limited by the solubility, and the slow diffusion will control the rate at which the gas passes the interface into the solution.

There are, of course, many gases and concentrations of gases in which the resistance of one of the films cannot be neglected and it is necessary to consider the effect of two resistances in series. With sufficient knowledge of the film thicknesses and diffusion and concentration data, this case can be solved also.

We may now consider the types of absorption surfaces available and show how they affect the rate of absorption.

Types of Gas Washers

Gas washers may be classified as follows: (*a*) liquid droplets traveling through a gas, (*b*) gas bubbles rising through a liquid, and (*c*) wetted surfaces over which a gas flows.

The liquid-droplet type is exemplified by the familiar spray washers. The droplets may be produced by forcing the liquid under high pressure through a nozzle, or by allowing the liquid to flow onto a rotating disk or wheel. The advantages of the latter type are the passage of large suspended solid particles without clogging and the production of very fine droplets without the use of high pressure. The mechanical wear and corrosion are often disadvantages. Both types, of course, produce very low draft losses. The high velocity of the drops through the gas gives a relatively thin gas film, so that this type of washer is most effective in absorbing highly soluble gases for which the thickness of the gas film controls the rate of absorption. The area of the absorbing surface per unit volume of liquid is inversely proportional to the size of the droplets.

A type of apparatus in which the gas bubbles rise through a liquid presents a very different condition from one in which liquid drops are sprayed through a gas. Here the bubble continuously exposes a fresh liquid surface so that the liquid film resistance is effectively reduced. This type of washer is most satisfactory for absorbing a gas of low solubility. Examples of bubble washers are found in the bubble-cap towers, used extensively in the oil industry, and in porous plate washers. Their chief disadvantage lies in the high draft loss due to the friction through the bubbler and the hydrostatic head of the liquid.

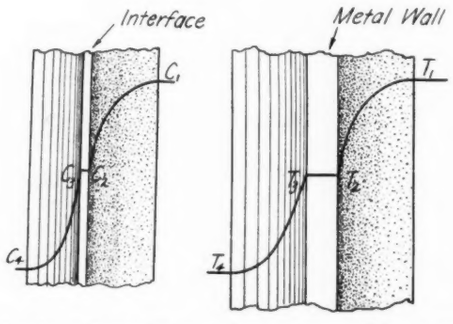


Fig. 1—Analogy between gas absorption and heat transfer.

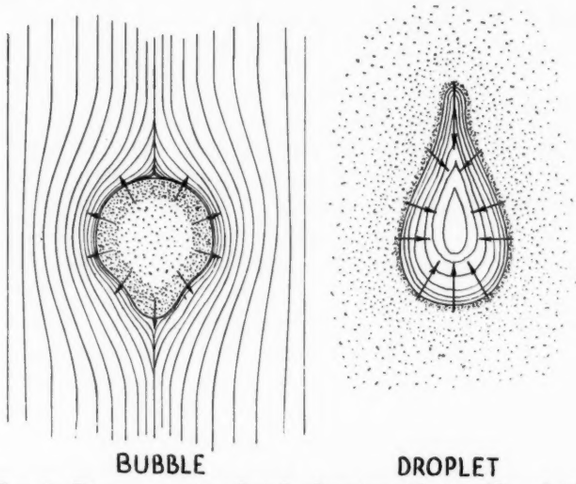


Fig. 2—Diagrammatic sketch showing relative film thicknesses in bubble and droplet.

A diagrammatic comparison of the conditions surrounding a drop and a bubble is shown in Fig. 2.

The wetted surface washer has been popular in the chemical industry for absorbing gases. In most cases some sort of packing material is used such as coke, quartz or manufactured stoneware of various shapes and sizes. The latter have the advantage of giving a large surface per unit volume. The weight of the material and frictional losses are often of considerable importance when very large volumes of gas are to be washed. Various types of wetted-wall washers have been designed for the removal of solid and liquid particles from gas streams. In general, these give only a relatively small contact as compared to that in a packed tower. While they may effectively remove dust from flue gases with only a small draft loss, they will be found of little use for absorbing the sulphur dioxide when untreated water is used.

Contact Required for Absorbing Sulphur Dioxide

In order to estimate the time and surface of contact required to absorb the sulphur dioxide, it is necessary to know the solubility of the gas and the film coefficients of the washer.

The concentration of sulphur dioxide in flue gas varies from 0.05 to 0.5 per cent by volume, depending on the type of fuel burned and the percentage of excess air used in the combustion. Table I shows a typical set of analyses obtained in a study of the gases from a high sulphur coal (*2*). It is to be noted that approximately 90 per cent of the sulphur in the coal is converted to sulphur dioxide and that, of the sulphur compounds in the gas, sulphuric acid vapor represents only about 3 per cent. The latter point is important because, if a large portion existed as the acid vapor, cleaning the gases would be a simple matter owing to the greater solubility of sulphuric acid in water. In fact, the removal could be accomplished in electrostatic precipitators used for dust precipitation.

The solubility in water of sulphur dioxide at such low concentrations has never been measured. These measurements are now in progress in our laboratory. The difficulties involved are considerable, but the exact values will be of great importance to industries interested in the problem of sulphur elimination. In the meantime, it will be satisfactory to use values extrapolated from higher concentrations with the understanding that they may be in error by 10 to 20 per cent.

In Fig. 3 these extrapolated data (*3*) for 68 fahr. are plotted

as curve AB showing the concentration in pure water in equilibrium with various concentrations in flue gas. Curve CD represents the solubility in water containing 100 parts per million alkalinity (as calcium carbonate) as calculated from the data for pure water. Evidently the solubility in ordinary surface waters will not exceed that in pure water by more than a few per cent.

Consider as a typical gas one containing 0.30 per cent sulphur dioxide, or 6.63 lb. SO_2 per 1000 lb. of flue gas. The maximum concentration of sulphur dioxide in the wash water will be only 0.79 lb. per 1000 lb. of water, and the maximum ratio of gas to water will be 0.118 lb. per lb., or roughly 12 cu. ft. per gal.

For absorption of a gas in a washer in which the resistance of the liquid film is large compared to that of the gas film, the rate may be expressed by

$$\frac{dW}{d\Theta} = AK_L (x - x_e) \qquad (1)$$

where A is the absorption area, sq. ft.

k_L represents the liquid film coefficient, expressed here in pounds per square foot per hour per unit concentration difference in pounds per pound of water

x is the concentration of the dissolved gas in the liquid at any point in the washer, pounds per pound of water

x_e is the corresponding equilibrium concentration.

From the data of Haslam, Ryan and Weber (*4*) for the absorption of sulphur dioxide by water in a spray tower, the resistance of the liquid film is 80 per cent of the total resistance at velocities of 0.5 ft. per sec., and reaches 96 per cent at 4 ft. per sec.

Evidently if the minimum quantity of water is used, an infinite time would be required to reach saturation. Let us assume that a counter-current washer is used and that only 80 per cent of the sulphur dioxide is removed, leaving 0.05 per cent in the exit gases. Also let the water leave the washer 90 per cent saturated in respect to the incoming gases, or carrying 0.71 lb. SO_2 per 1000 lb. of water. The line EF then represents the conditions in the washer regardless of the type of apparatus, or time or intimacy of contact.

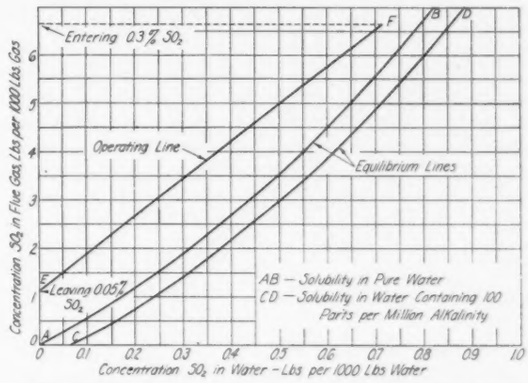

Entering 0.3% SO2
Operating Line
Equilibrium Lines
Leaving 0.05% SO2
AB — Solubility in Pure Water
CD — Solubility in Water Containing 100 Parts per Million Alkalinity
Concentration SO2 in Flue Gas, Lbs per 1000 Lbs Gas
Concentration SO2 in Water - Lbs per 1000 Lbs Water

Fig. 3—Solubility of sulphur dioxide at 68 fahr.

The average value of $(x - x_e)$, found by graphical integration (by plotting x against $1/(x - x_e)$), is 0.000158 lb. SO_2 per lb. of water.

The value of k_L for droplets has not been determined, but it should be approximately equal to the liquid film coefficient for a liquid only slightly stirred. We shall take the value 5.58 derived from the data of Becker (*5*) for his slowest rate of stirring, 60 r.p.m. In the units here employed this coefficient under conditions of equal film thickness, is the same for all substances. It is also independent of the gas velocity past the droplet. The rate of absorption of sulphur dioxide in a spray washer, therefore, is

$$W = 5.58 \times 0.000158 = 0.00088 \text{ lb. per sq. ft. per hr.}$$

The total quantity of sulphur dioxide absorbed per cu. ft. is 0.00045 lb. The contact required for the absorption, therefore, is 1830 sq. ft. sec. per cu. ft.*

* Contact is expressed as area × time per unit volume of gas.

TABLE I—TYPICAL COMPOSITION OF FLUE GASES FROM A HIGH SULPHUR COAL

Coal Analysis, "As Received" Basis

	%		%
Moisture	14.5	Oxygen	7.01
Carbon	55.6	Nitrogen	1.13
Hydrogen	3.86	Sulphur	4.45

Coal Burned on Chain Grate Stoker

Boiler	Point of Sampling	Distance from Front, Ft.	Distance from Side, Ft.	No. Samples	SO_2, %[b]	SO_3, %	O_2, %	CO_2, %	Ratio, S:C[c]	S as SO_3, %
1	First pass of boiler	4	5	2	0.289	0.0060	8.6	10.8	0.073	2.0
	First pass of boiler	4	10	2	0.313	0.0086	7.8	11.6	0.074	2.7
	First pass of boiler	6	10	2	0.300	0.0122	8.0	11.5	0.072	3.9
2	First pass of boiler	2	5	2	0.295	0.0060	...	12.6	0.064	2.0
	First pass of boiler	2	10	3	0.347	0.0018	...	14.2	0.067	3.3
	First pass of boiler	4	5	3	0.384	0.0030	...	13.1	0.079	0.8
	First pass of boiler	4	10	3	0.373	0.0143	4.1	15.0	0.069	3.8
	First pass of boiler	6	5	4	0.279	0.0123	...	12.1	0.064	3.9
	First pass of boiler	6	10	2	0.328	0.0148	...	12.8	0.071	4.3
	Second pass of boiler	10	5	3	0.268	0.0154	...	9.6	0.078	5.5
	Second pass of boiler	10	10	3	0.346	0.0126	...	13.0	0.074	3.6
	Economizer outlet	2	5	3	0.270	0.0050	9.0	10.9	0.068	1.8
	Economizer outlet	2	10	2	0.274	0.0050	9.5	10.0	0.075	1.8
	Induced fan inlet	.	2	6	0.100	0.0019	15.6	4.4	0.063	1.9
3	First pass of boiler	4	5	2	0.156	0.0016	...	5.4	0.078	1.2
	First pass of boiler	4	10	3	0.197	0.0059	10.8	8.0	0.075	2.7
	First pass of boiler	6	5	2	0.207	0.0035	11.8	7.8	0.073	1.6
	First pass of boiler	6	10	3	0.319	0.0086	7.5	11.5	0.074	2.6
	Second pass of boiler	10	5	3	0.268	0.0035	9.3	10.1	0.072	1.4
	Second pass of boiler	10	10	3	0.274	0.0152	9.0	10.6	0.073	5.3
	Economizer outlet	2[a]	5	3	0.240	0.0071	11.4	8.6	0.073	2.9
	Economizer outlet	2[a]	10	3	0.272	0.0068	9.7	10.2	0.073	2.4
	Economizer outlet	2[a]	15	3	0.317	0.0079	8.0	11.7	0.074	2.4
	Average	.	.	.	0.279	0.0082	...	10.7	0.072	2.8
	Coal Burned in Pulverized Fuel Boiler									
4	First pass of boiler	4	5	3	0.414	0.0046	5.0	14.3	0.078	1.1
	First pass of boiler	4	10	3	0.387	0.0027	4.0	15.3	0.068	0.7
	First pass of boiler	8	5	3	0.421	0.0032	5.9	13.3	0.085	0.8
	First pass of boiler	8	10	3	0.453	0.0034	3.6	15.6	0.078	0.7
	Economizer outlet	.	5	2	0.479	0.0036	5.0	14.2	0.090	0.8
	Economizer outlet	.	10	2	0.416	0.0032	6.3	12.9	0.086	0.6
	Economizer outlet	.	5	3	0.347	0.0020	8.2	11.1	0.085	0.6
	Induced fan inlet	.	4	4	0.385	0.0028	7.6	11.8	0.087	0.7
	Average	.	.	.	0.413	0.0032	5.7	13.6	0.082	0.8

[a] From top of duct between economizer and preheater.
[b] All percentages are by volume.
[c] Ratios are by weight.

TABLE II—COMPARISON OF WASHER TYPES FOR ABSORPTION OF SULPHUR DIOXIDE FROM FLUE GAS BY WATER

Basis of Calculation	Type of Washer: Spray	Bubble	Wetted-Wall
	0.02 in. drops	1/8 in. bubbles	3 × 3 in. spiral packing
Composition of gas			
% SO_2 entering	0.30	0.30	0.30
% SO_2 leaving	0.05	0.05	0.05
Temperature, deg. fahr.	68	68	68
Gas velocity, ft. per sec.	1	0.1	2
Water required, gal. per 10^6 cu. ft.	75,000	75,000	75,000
Rate of absorption, lb. per hr. per 1000 sq. ft.	0.88	0.55	1.61
Contact required, sq. ft. sec. per cu. ft.	1830	2900	910
Time of contact required, sec.	51	4	19
Approximate size of washer for 10^6 cu. ft. per min., cu. ft.	860,000	280,000	525,000
Sq. ft. contact per gross cu. ft. of washer	35	172	29
Percentage of free space in washer	99	24	60
Height, ft.	51	0.4	38
Approximate draft loss, in. of water	0.1	12	2

If the spray produces droplets of 0.02 in. dia., the total surface per gallon is 480 sq. ft., and since each cubic foot of gas requires 0.075 gal. the time of contact required will be 51 sec.

The size assumed for the droplets is approximately the minimum produced by spray washers and any smaller size is readily carried as mist by a moving gas. We may conclude that this time of contact will be approximately the minimum for straight absorption of sulphur dioxide in untreated water when the water leaves the washer 90 per cent saturated.

For a bubble washer, in which the resistance of the liquid film is negligible compared to that of the gas film, the rate of absorption is given by

$$\frac{dW}{d\Theta} = Ak_G\Delta p, \qquad (2)$$

where k_G is the gas film coefficient, expressed here in pounds per square foot per hour per unit concentration difference in the gas film in atmospheres pressure.

The value of $\Delta p_{av.}$ may be found from the average value of $(y_e - y)$, where y is the concentration of SO_2 in the gas at any point in the washer, in pounds per pound of gas, and y_e is the corresponding equilibrium concentration.

The average value of $(y_e - y)$ found by a graphical integration similar to that described above is 0.00121, whence $\Delta p_{av.} = 0.00055$ atm.

The value of the coefficient, k_G, is derived from the relative resistance of the films as measured by Haslam, Ryan and Weber (*6*) for absorption in a wetted-wall washer for very low gas velocities, and from the data of Adeney and Becker (*7*) on absorption by bubbles. These indicate that the resistance of the gas film in this case is at least 90 per cent of the total resistance and that the approximate value is 1.0.

The rate of absorption of sulphur dioxide in a bubble washer, therefore, is

$$W = 1.0 \times 0.00055 = 0.00055 \text{ lb. per sq. ft. per hr.}$$

The contact required to remove 80 per cent of the sulphur compounds from a cubic foot of gas is 2700 sq. ft. sec.

In a similar manner, the contact required by a wetted-wall washer, in which the resistance of both films must be considered, is approximately 910 sq. ft. sec. per cu. ft. (*8*). This value is based on a gas velocity of 2 ft. per sec.

A summary of these calculations is shown in Table II, together with other data based on these values. The figures given can be considered only as approximate, but they afford a good comparison for the various types of washers.

While the spray type washer gives the least draft loss and is second only to the wetted-wall washer in respect to contact required, as a result of the rather small surface attainable per unit volume, the gross dimensions of this washer are considerably larger than those of any of the three types considered. The wetted-wall washer requires a small contact but, again on account of the small surface available per unit volume, its size is still large. The draft loss through this washer is proportional to its height and to the square of the gas velocity. The gas velocity chosen gives a draft loss within possible consideration.

The values given for the bubble type washer are based on observations made on a small experimental washer in which a porous plate was used to form the bubbles. The difficulty of handling dust-laden gas in this case is apparent. In spite of the large contact required by this washer, the time is reduced to a relatively small value because of a large surface per unit volume. A depth of 5 in., therefore, is sufficient to remove the sulphur dioxide. Even this, however, with the friction of the plate causes a draft loss that is an economical barrier. This type of washer requires only 33 per cent of the gross volume required by a spray washer.

TABLE III—ABSORPTION OF SULPHUR COMPOUNDS IN FLUE GASES BY COLD WATER—GROVE ROAD POWER STATION TESTS

Gas Velocity, Ft. per Sec.	Time of Contact, Sec.	Sulphur Content % SO_2 by Volume: Before	After	Removal, %	Concentration in Effluent Water, Lb. SO_2 per 1000 Lb. Water	Water Used, Gal. per 1000 Cu. Ft. Gas
Water-flow 1900 gal. per hr.						
1.9	14	0.043	0.000	100	0.29	30.8
2.2	12	0.038	0.000	100	0.28	29.2
2.9	9	0.038	0.002	94	0.35	20.9
3.4	8	0.030	0.002	90	0.32	17.8
3.6	7	0.027	0.007	78	0.26	16.8
3.8	7	0.025	0.007	73	0.24	15.9
2.2	12	0.062	0.007	90	0.42	27.5
3.0	9	0.057	0.009	84	0.50	20.2
1.9	14	0.112	0.000	100	0.76	31.8
3.6	7	0.080	0.032	59	0.60	16.8
Water-flow 1100 gal. per hr.						
1.8	13	0.039	0.005	87	0.36	19.4
3.0	9	0.031	0.006	82	0.45	11.7
2.5	12	0.097	0.035	64	0.86	15.2
2.9	9	0.098	0.025	74	1.27	12.1
2.9	9	0.094	0.059	37	0.60	12.1
3.6	7	0.103	0.048	53	1.18	9.7
3.6	7	0.093	0.038	59	1.18	9.7
2.2	12	0.088	0.022	76	1.02	14.1
2.3	11.5	0.121	0.032	73	1.39	13.3
2.3	11.5	0.091	0.009	90	1.30	13.3
3.1	9	0.123	0.011	91	2.40	9.8
3.2	8.5	0.126	0.032	75	2.06	9.5
3.3	8	0.090	0.012	86	1.75	9.2
3.6	7	0.137	0.023	83	2.83	8.5

TABLE IV—ABSORPTION OF SULPHUR COMPOUNDS IN FLUE GASES BY HOT WATER—GROVE ROAD POWER STATION TESTS

Gas Velocity, Ft. per Sec.	Time of Contact, Sec.	Sulphur Content % SO_2 by Volume: Before	After	Removal, %	Concentration in Effluent Water, Lb. SO_2 per 1000 Lb. Water	Water Used, Gal. per 1000 Cu. Ft. Gas
Water-flow 720 gal. per hr.						
1.8	15	0.028	0.0011	96	0.43	12.9
1.9	14	0.017	0.0016	91	0.27	12.0
1.9	14	0.032	0.0096	72	0.44	12.0
2.1	13	0.025	0.0018	93	0.47	10.9
2.2	12	0.037	0.0016	96	0.73	10.4
2.4	11	0.028	0.0021	93	0.58	9.5
2.8	9.5	0.029	0.0021	93	0.71	8.2
2.8	9.5	0.021	0.0041	80	0.44	8.2
3.1	9	0.024	0.0021	91	0.64	7.4
3.4	8	0.013	0.0021	84	0.35	6.8
3.5	7.5	0.015	0.0030	81	0.40	6.5
3.6	7	0.028	0.0030	89	0.85	6.4
2.2	12	0.105	0.0149	86	1.85	10.4
2.9	9	0.116	0.0119	90	2.83	7.9
3.7	7	0.119	0.0162	86	3.56	6.2

Tests Made by London Power Company

In the light of the above discussion it will be interesting to consider the tests made at the Grove Road Power Station in England and the design of the washing system for the Battersea Station based on these results. These data constitute the only published results of large scale tests on the removal of sulphur dioxide from flue gas (*9*).

The washer used in these tests consisted of a cylindrical absorption tower, 27 ft. high and 40 in. in dia. The flue gases were drawn from a stack through a 12-in. pipe to the base of the tower. In a part of the experiments, untreated tap water was used, entering the tower at 68 fahr., and leaving at 85 fahr., without recirculation. The water was delivered to three spirals, each carrying about 40 spray nozzles at heights of 10, 17 and 24 ft., respectively. A portion of the tower

between the two upper sprays was packed with spiral absorption rings.

The results of the tests using cold water are shown in Table III. While the concentration of sulphur compounds, calculated from the ratio of gas to water, and expressed as lb. of sulphur dioxide per lb. of water, in contact with the incoming gases, exceeds that indicated by the equilibrium curve in Fig. 3 in all cases, and for some tests by as much as fourfold, the total quantity of water required agrees in order of magnitude with that calculated. This excess solubility of the sulphur dioxide is considerably greater than the possible error in the equilibrium curve and indicates that a secondary reaction was taking place after the gas dissolved, i.e., interaction with an alkaline agent or with dissolved oxygen, the latter to form sulphuric acid. That this reaction did not increase the total absorption rate, however, is indicated by the time of contact required to remove the relatively small amount of sulphur dioxide.

The effect of this secondary oxidation reaction on the capacity of the water was even more striking when hot water was used for washing the gases. Since the solubility of a gas in water decreases with increase in temperature, more water should be required as the temperature is raised if the sulphur dioxide is removed by simple absorption. The reverse of this was found to be true, however, when water at 145 fahr. was used in the same experimental outfit. Some of the results are shown in Table IV. The concentration of sulphur compounds, expressed as pounds sulphur dioxide per pound of water, in the effluent water in contact with the incoming gases, is greater than the corresponding values for cold water and greatly exceeds the values for an equilibrium curve for 145 fahr. This indicates that the oxidation is more rapid and complete at the higher temperature. The absorption rate, however, is not greatly increased.

As a result of these, and of other tests made with different types of contact surfaces, the following conclusions were drawn:

"1. The process must be thought of in two phases, conversion of SO_2 to SO_3 and elimination of SO_3 and residual SO_2; each of course interlaps or merges into the other, and there can be no sharp line of demarcation.

"2. While the dust in the gas acts as a powerful catalyst, there is not sufficient quantity to affect the whole of the gas in the period under treatment, and as a very large proportion of the dust is eliminated in the early stages, there is a diminishing quantity in contact with the gas to effect conversion of SO_2 to SO_3.

"3. Iron in the form of oxides, not any particular oxide, but oxides whose equilibrium will become adjusted with the gas phase in the plant, must be present at all stages from the first contact of gas and water to the final elimination from the gas and in the effluent. For this purpose it appears necessary to utilize iron or steel metal surfaces which become oxidized in the gas stream, and so adapted to the work to be performed.

"4. For intimate contact of gas and water, it is necessary to have:

(*a*) Fine sprays of water, and
(*b*) Wetted surfaces to break up stream lines, and to assist the conversion of SO_2 to SO_3, certainly the latter, and these surfaces must not be of a reducing nature.

"5. Hot water is preferable to cold water, for conversion of SO_2 to SO_3, and for retaining the temperature of the gas.

"6. There is a critical time of contact between gas and water, under each set of physical conditions, below which it is not advisable to work; these physical conditions include:

(*a*) Directions of flow of gas and water
(*b*) Speed of gas travel
(*c*) Amount and disposition of wetted iron surfaces
(*d*) Amount and disposition of other wetted surfaces
(*e*) Temperatures of gas and water
(*f*) The degree of alkalinity of the water.

"7. There would appear to be a critical temperature of the gas for conversion of SO_2 to SO_3, depending upon conditions similar to those enumerated above."

The Battersea Station

Based on the foregoing conclusions, the design of the washer for the new Battersea plant, which is shown in Fig. 4, calls for the use of 25 tons of water per ton of coal. The time of contact ranges from a minimum of 23 seconds to a maximum of 44 seconds. "Since recirculation does not assist in the removal of the sulphur compounds, due to the increased acidity of the water which thereby results, the water will be kept as nearly neutral as possible at each stage." In addition to these, the plant will also provide

"(*a*) A low velocity of the gases
(*b*) Initial humidification of the gases by means of atomizers or sprays

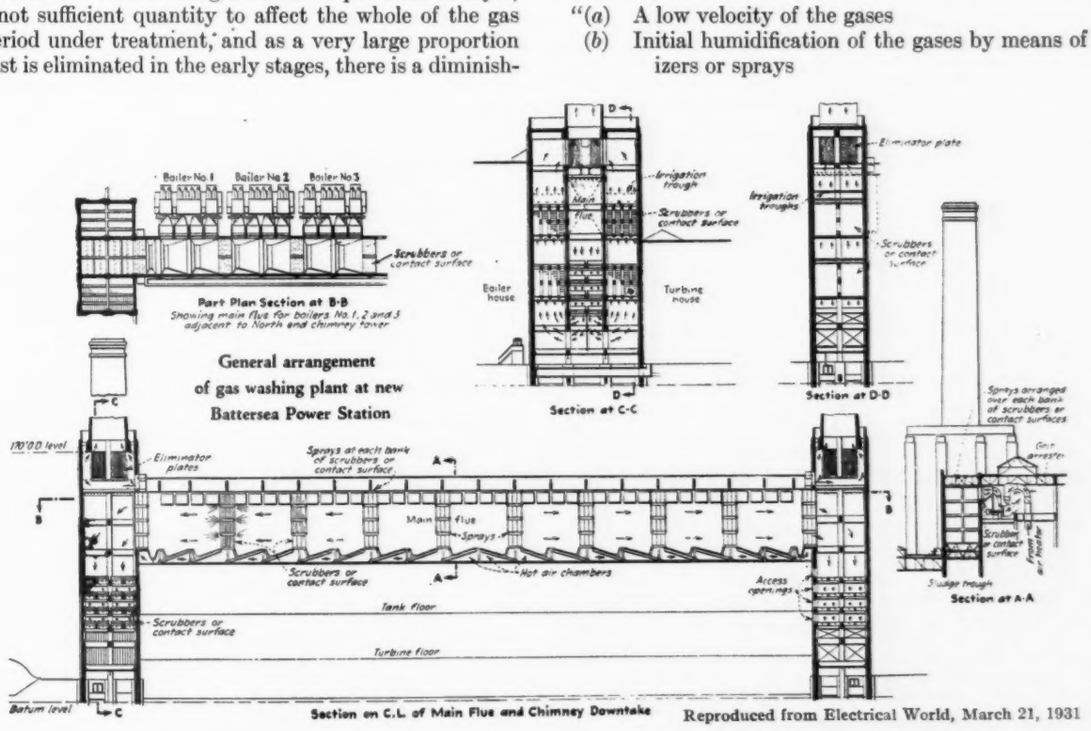


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Fig. 4—General arrangement of gas washing plant at new Battersea Power Station.

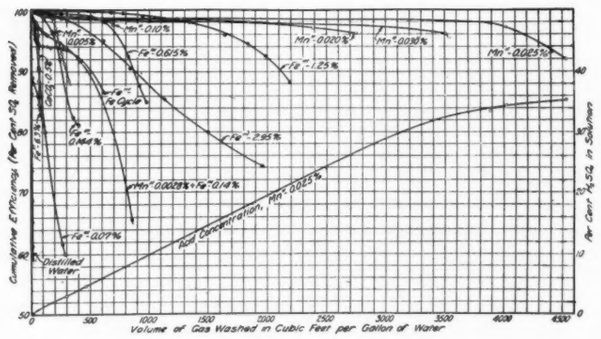

Fig. 5—Effect of metallic ions on capacity of water for absorbing sulphur dioxide from air mixtures containing 0.325 per cent sulphur dioxide—bubble type washer.

(*c*) The provision of wetted surfaces of iron or steel to assist in the conversion of SO_2 to SO_3

(*d*) Complete washing of the gases to remove acidulated water

(*e*) The further provision of surfaces wetted with cold and alkaline water for the final and total elimination of sulphur from the gas

(*f*) Ample time of contact between the flue gases and the washing water

(*g*) The change in direction of the path of the gases

(*h*) The admission of hot dry air at the base of the chimney proper to mingle with the supersaturated gases with a view to avoid condensation in cold weather

(*i*) The provision for the introduction of suitable catalysts into the spray and wash waters, as may be found desirable

(*j*) The provision of suitable linings for the chambers through which the gases pass

(*k*) The recirculation of the spray and wash water or other liquid, if found desirable

(*l*) Means for the removal of sludge or other deposits

(*m*) Means for replacing the materials that may be subjected to wasting

(*n*) Complete oxidation of the effluent, if found necessary."

The wash water from the plant is to be mixed with the condenser water (of which the latter is about 40 times the former) to neutralize the acidity and the mixture returned to the river. The alkalinity of the river is approximately 200 parts per million. The corrosion problem is, of course, a difficult one. For the circulating pumps and other parts in contact with the wash water, use of an alloy of silicon and copper, cast iron or monel metal is planned.

The cost of such an operation, including the limited use of a lime alkali in the final stages of the process, is estimated to be approximately 1/6 d. (37 cts.) per ton of coal burned.

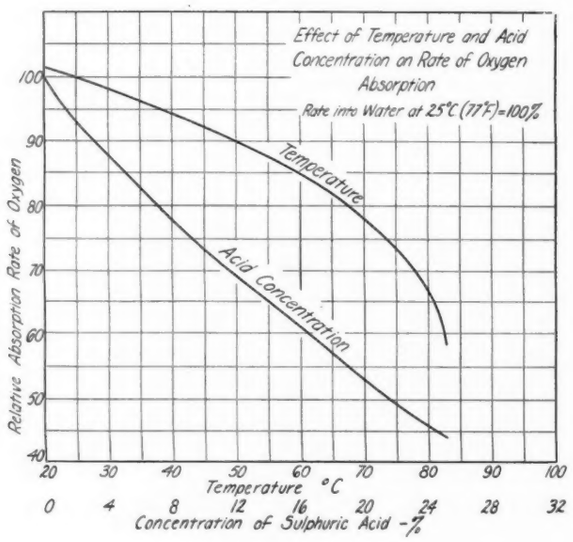
Effect of Temperature and Acid Concentration on Rate of Oxygen Absorption
Rate into Water at 25°C (77°F)=100%
Temperature
Acid Concentration
Relative Absorption Rate of Oxygen
Temperature °C
Concentration of Sulphuric Acid - %

Figure 6

Catalytic Oxidation of Dissolved Sulphur Dioxide

Because of the important effect of the oxidation on the capacity of the water for absorbing sulphur dioxide, this reaction has been investigated in some detail. The results differ in a few points from the conclusions drawn by the

TABLE V—EFFECT OF CATALYSTS ON THE ABSORPTION OF SULPHUR DIOXIDE FROM AIR-SO_2 MIXTURES—BUBBLE WASHER

Gas Flow 0.64 c.f.m.—Contact Approximately 1200 Sq. Ft. Sec. per Cu. Ft.; SO_2 = 0.325%

Gas Washed, Cu. Ft. per Gal.	% SO_2 Removed	Cumulative Efficiency, %	Acid Concentration, % H_2SO_4
	Distilled Water		
5.9	86.4	86.4	..
7.6	52.6	76.5	..
9.0	43.8	73.5	..
10.2	35.7	68.7	..
12.4	26.8	61.4	..
	Catalyst—25 p.p.m. manganese		
31.4	96.1	96.1	..
38.7	83.6	93.7	..
43.8	76.3	91.7	..
48.9	75.6	90.1	..
69.3	66.7	84.3	..
88.5	58.3	79.4	0.74
	Catalyst—100 p.p.m. manganese		
154	99.2	99.2	1.7
339	98.6	98.9	4.3
575	97.0	98.5	6.1
675	93.6	98.2	6.8
691	68.7	97.5	6.9
	Catalyst—150 p.p.m. manganese		
177	98.6	98.6	0.9
375	98.8	98.7	3.9
684	98.7	98.8	6.9
850	98.4	98.7	8.5
1319	97.4	98.2	12.2
1572	93.0	97.6	14.8
1730	89.7	97.0	16.0
1894	82.1	96.0	17.1
2009	50.0	95.4	18.0
	Catalyst—250 p.p.m. manganese		
100	98.9	98.9	1.1
364	98.2	98.7	3.7
3500	98.5	98.5	..
3886	89.0	97.8	33.2
4020	47.0	97.2	33.9
4530	20.0	92.0	35.0
	Catalyst—300 p.p.m. manganese		
131	99.1	99.1	1.3
359	98.4	98.6	3.9
615	98.1	98.4	6.4
3510	40.0	96.1	29.6
	Catalyst—250 p.p.m. manganese Temperature—140 Deg. Fahr.		
284	95.8	95.8	2.7
559	90.2	93.0	6.0
1380	80.4	85.6	13.1
2040	80.0	82.5	21.0
2090	40.0	81.4	22.3
	Catalyst—0.070% Iron		
36	96.8	96.8	0.4
66	90.7	76.8	0.6
121	80.0	64.3	1.0
	Catalyst—0.283% Iron		
114	98.9	98.9	1.2
273	92.8	96.0	2.7
520	77.0	87.9	4.8
739	73.0	82.4	6.3
	Catalyst—1.25% Iron		
530	99.8	99.8	5.5
778	98.8	99.5	8.0
942	94.7	99.0	9.0
1233	96.1	98.5	12.1
1640	80.0	95.9	15.3
1985	54.5	92.5	17.7
	Catalyst—2.95% Iron		
170	99.2	99.2	1.8
226	97.3	98.9	2.4
612	86.0	95.0	7.0
835	78.0	90.5	7.7
1130	63.0	85.5	9.7
1498	60.0	80.0	12.0

investigators of the London Power Company and indicate the limitations of the method.

It was important to determine if there was catalytic oxidation of the gaseous sulphur dioxide (SO_2) to the sulphuric anhydride (SO_3), or whether the oxidation takes place after the dioxide is dissolved. If the former were the case, it should be possible to obtain fast absorption of the very soluble sulphuric acid vapors in very small quantities of water. If the oxidation takes place after dissolution, however, the limiting rate of oxidation is the rate of absorption of the necessary oxygen and, while the total quantity of water may be reduced, the contact required will still be large.

The use of various metallic oxides as catalysts for the oxidation of gaseous sulphur dioxide is common in the sulphuric acid industry. Of these, the oxides of iron are only mildly active (*10*). The activity has a sharp temperature optimum, above and below which it drops off rapidly. It is also subject to catalytic poisons, although not to the extent of platinum catalysts.

In a study of the reactions of sulphur compounds in boiler furnaces, made in connection with a corrosion study, it was found that there is no increase in the proportion of the sulphur gases in the oxidized form of sulphur trioxide as the gases passed over the hot tubes and slag in the boiler and the colder surfaces in the economizer and air preheater (*11*). The data given in Table I are representative of these results. No indication of catalytic action is to be noted.

In order to confirm this, a sample of flue dust containing 39.5 per cent iron oxide (Fe_2O_3) was maintained under carefully controlled conditions of temperature and gas flow in the presence of a mixture of air and sulphur dioxide containing 0.428 per cent SO_2. The rate of flow was 250 cc. per minute per gram of dust. The results showed that the oxidation is small in all cases and reaches a maximum near 400 cent. (750 fahr.) when 1.8 per cent of the sulphur dioxide is converted to the trioxide. We conclude, therefore, that the possibilities of dust, or iron surfaces, for converting sulphur dioxide to sulphur trioxide is very small.

In a further study of the corrosion problem, however, the strong catalytic properties of *solutions* of iron salts were noted in connection with the formation of sulphuric acid from the sulphur dioxide. This takes place readily in the colder parts of economizers and preheaters, where condensation occurs and dissolves the iron salts in the deposits of flue dust. This action agrees with that noted by Ralston, and others, for the catalytic action of solutions of ferrous sulphate in the oxidation of *dissolved* sulphur dioxide (*12*).

With this work as a background, a thorough study of the catalytic action of various salts was made to determine their effect on the absorption of sulphur dioxide from dilute gases and the possibilities of their use. These experiments were made on an air-sulphur dioxide mixture containing, in general, 0.325 per cent SO_2. A bubble type washer in which the bubbles

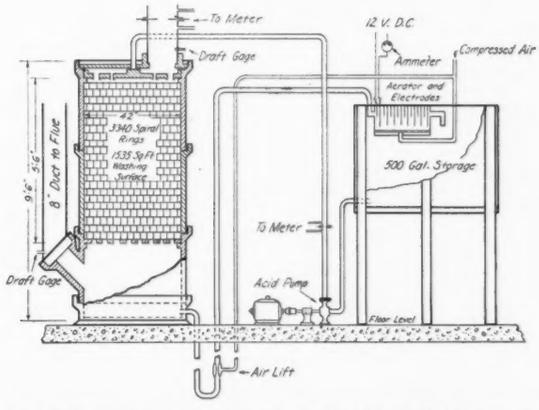

Fig. 7—Gas washing system for catalytic oxidation method.

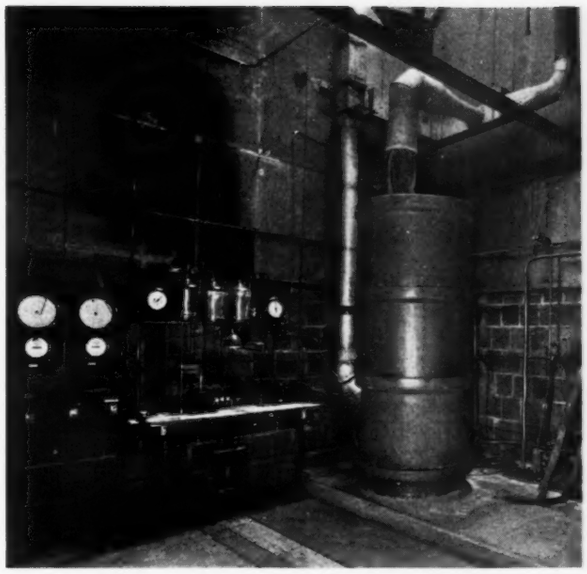

Fig. 8—View of experimental gas washing plant.

were formed by passage through a porous Filtros C plate was used for the laboratory experiments. The following description of the washer is given for comparison purposes:

Area of plate, 12.5 sq. in.
Thickness of plate, 1/2 in.
Per cent of pore space, by volume, 30.2
Resistance of saturated plate when passing

Cu. ft. per sq. ft. per min.	2	4	8
In. of water	7	8	12

Average size of bubbles, 1/8 in.
Elevation in water level due to bubbles, 3 in.
Rate of gas flow, 0.638 cu. ft. per min.
Area of bubbles, 1810 sq. in.
Time of contact, 2.0 sec.
Contact units, 1180 sq. ft. sec. per cu. ft.
Coefficient of free space, cu. ft. per cu. ft. water, 0.24
Coefficient of surface, sq. ft. per cu. ft. water, 172.

The results of these tests are shown in Table V and Fig. 5 (*13*). Of a large number of salts tested for catalytic action, those of iron and manganese were the most promising. The activity of the latter was nearly 100 times that of the former. The capacity of the water for absorbing the sulphur compounds due to the catalytic oxidation was about 200 times that of pure water. The action, of course, produced sulphuric acid which, under the best conditions, reached 40 per cent concentration.

A summary of other conditions affecting the catalytic action follows:

(1) With increasing catalyst concentration the efficiency of the washer increased rapidly until a certain critical point was reached. Above this the concentration had little effect on the dilute acid ranges and actually decreased the efficiency in the more concentrated acid solutions. These critical concentrations were approximately 1.2 per cent for iron and 0.025 per cent for manganese. The explanation for this is evidently that the catalyst continues to increase the rate of oxidation until it uses up the oxygen as fast as it is absorbed.

(2) Below the critical catalyst concentration an increase in temperature increases the efficiency of the washer because it increases the rate of reaction, but above the critical concentration it decreases the efficiency due to decrease in the solubility of oxygen.

(3) A decrease in the oxygen content of the gases lowers the efficiency of the washer and the critical catalyst concentration. A decrease in sulphur dioxide concentration has the opposite effects.

(4) In the case of iron salts as catalysts the capacity of the solution is greatly increased by circulating the solution over scrap iron, whereby the concentration of the catalyst is increased and that of the acid decreased.

These results agree, in general, with the observations made in the Grove Road tests. One important difference is to be noted, however, that throws a different aspect on the limitations of the use of catalysts. The oxidation takes place after the sulphur dioxide is dissolved and not before. Evidently the use of large surfaces of iron only increases the supply of catalyst in the solution. It is necessary to dissolve an equivalent amount of oxygen (equal to one-fourth the weight, or one-half the volume of sulphur dioxide) along with the sulphur dioxide in order to secure oxidation. When this oxygen is absorbed the capacity of the water is increased considerably. Unfortunately, the rate of oxygen absorption is slower than that of sulphur dioxide into a solution devoid of sulphur dioxide, and this factor limits the rate of solution in this case. It will, therefore, be of interest to consider the conditions affecting the rate of oxygen absorption from flue gases.

TABLE VI—ABSORPTION OF SULPHUR DIOXIDE FROM FLUE GASES IN PACKED TOWER WASHER USING CATALYTIC OXIDATION METHOD

400 gal. water containing 250 p.p.m. manganese

Series 1—Gas velocity 58 c.f.m.—Water circulation 16 g.p.m. Time of contact—35 sec.

1	2	3	4	5	6	7	8	9	10
Time, Hr.	Total Volume Washed, 1000's Cu. Ft.	% CO_2	% O	% SO_2 Entering	% SO_2 Leaving	% H_2SO_4 in Water	Temp. Water, Deg. Cent.	$\frac{W_s}{\Theta}$ $k_s.k_L.b \times 10^3$	% SO_2 Removed
1.2	4.1	7.1	12.6	0.165	0.007	0.160	22.2	2.27	96
4.3	15.1	8.0	11.1	0.158	0.017	0.345	30.8	2.40	89
5.5	19.1	6.2	13.0	0.150	0.022	0.425	32.7	1.88	85
6.1	21.2	7.2	12.4	0.157	0.014	0.45	34.0	2.22	91
7.0	24.3	6.0	13.4	0.127	0.009	0.48	34.5	1.85	93
12.0	41.8	7.3	12.0	0.145	0.017	0.78	37.5	2.09	88
14.0	48.8	7.6	11.6	0.145	0.024	0.90	37.8	2.05	83
15.0	52.2	6.6	13.6	0.148	0.016	0.97	37.5	1.92	89
16.0	55.7	7.1	12.4	0.143	0.020	..	37.5	1.96	86
17.0	59.2	6.0	13.8	0.143	0.017	1.04	38.0	1.81	88
18.0	62.7	6.4	13.4	0.143	0.017	..	37.5	1.87	88
19.0	66.2	7.0	12.5	0.142	0.024	1.18	38.0	1.87	83
20.0	69.7	6.0	13.6	0.113	0.013	..	38.0	1.47	89
21.0	73.1	6.0	13.6	0.127	0.015	1.28	38.0	1.65	88
22.0	76.6	8.0	12.2	0.139	0.026	..	38.0	1.86	81
25.0	87.0	7.4	12.6	0.140	0.023	1.54	39.2	1.89	84
26.0	90.5	6.8	13.0	0.130	0.020	..	39.3	1.79	85
27.0	94.0	7.0	12.9	0.133	0.020	1.61	40.0	1.79	85
28.0	97.5	6.4	13.4	0.149	0.032	..	40.2	1.79	79
29.0	101.0	6.5	13.5	0.134	0.022	1.88	40.0	1.71	84
30.0	104.5	6.4	13.5	0.133	0.019	..	40.0	1.74	81
31.0	107.9	6.8	13.2	0.144	0.020	1.91	40.3	1.97	86
32.0	111.4	6.9	12.6	0.130	0.017	..	41.5	1.86	87
38.0	132.3	6.0	13.8	0.107	0.014	..	40.5	1.41	87
39.0	135.8	5.8	14.0	0.099	0.014	2.14	40.0	1.26	86
40.0	139.0	7.0	12.6	0.129	0.022	..	39.5	1.77	83
41.0	143.0	6.3	13.7	0.104	0.014	2.29	38.5	1.36	87
42.0	146.0	5.8	14.2	0.104	0.015	..	38.5	1.30	86
43.0	150.0	5.9	14.0	0.118	0.014	2.39	38.5	1.51	88
44.0	153.0	5.8	14.2	0.105	0.031	..	38.0	1.09	70
45.0	157.0	5.9	14.1	0.098	0.016	2.55	38.0	1.22	84
46.0	160.0	5.9	13.8	0.123	0.020	..	38.5	1.57	84
47.0	164.0	7.1	12.6	0.112	0.020	2.62	39.0	1.54	82
48.0	167.0	6.8	13.0	0.114	0.021	..	40.0	1.51	82
49.0	171.0	7.6	11.9	0.149	0.034	2.72	40.0	2.05	77
50.0	174.0	7.4	11.6	0.182	0.072	..	40.0	2.01	60
Average		6.7	13.0	0.132	0.020	..	37.8	1.76	85

Series 2—Gas velocity 97 c.f.m.—Water circulation 16 g.p.m. Time of contact—21 sec.

1.6	9.2	7.2	12.3	0.128	0.022	0.27	28.0	2.70	83
2.6	15.1	6.6	12.6	0.153	0.039	0.33	33.5	2.80	75
3.6	20.9	5.8	13.8	0.126	0.023	0.41	36.0	2.41	82
4.6	26.7	6.1	13.4	0.123	0.028	0.48	38.3	2.32	77
5.6	32.6	6.2	13.6	0.113	0.024	0.54	40.0	2.17	79
6.6	38.4	6.1	13.3	0.114	0.025	0.60	41.3	2.24	78
7.6	44.2	7.0	12.3	0.134	0.044	0.67	41.5	2.43	67
8.6	50.1	6.8	12.9	0.113	0.036	0.74	42.3	2.01	69
9.6	55.9	6.0	13.8	0.115	0.027	0.81	42.0	2.15	77
10.6	61.8	9.6	10.4	0.160	0.061	0.88	44.3	3.17	62
11.6	67.5	7.0	12.6	0.115	0.038	0.93	43.5	2.07	67
12.6	73.5	5.6	14.6	0.132	0.048	1.01	41.5	1.94	64
13.6	79.2	6.0	14.0	0.096	0.020	1.06	42.0	1.85	79
14.6	85.0	6.2	13.8	0.115	0.034	1.13	41.5	1.99	70
16.6	96.8	6.2	13.8	0.138	0.041	1.25	42.0	2.31	70
Average		6.6	13.1	0.125	0.034	..	39.8	2.30	73

Series 3—Gas velocity 138.5 c.f.m.—Water circulation 15.5 g.p.m. Time of contact—14.7 sec.

0.9	7.6	6.9	12.5	0.153	0.079	0.22	34.0	2.80	48
2.0	16.6	6.5	12.7	0.149	0.046	0.32	39.0	3.83	69
2.8	24.3	6.7	13.0	0.149	0.043	0.39	41.0	3.90	71
3.9	32.5	6.8	12.8	0.147	0.056	0.47	43.0	3.45	62
4.9	40.8	7.0	12.7	0.141	0.060	0.54	43.5	3.09	57
5.9	49.1	7.3	11.8	0.153	0.081	0.62	44.5	2.99	30
6.9	57.5	7.5	11.7	0.145	0.111	0.68	45.0	1.86	19
Average		7.1	12.4	0.148	0.068	..	41.5	3.12	54

Series 4—Gas velocity 204 c.f.m.—Water circulation 18.2 g.p.m. Time of contact—10.0 sec.

1.4	17.3	7.0	12.6	0.141	0.106	0.23	34.5	1.86	21
3.4	41.8	7.1	12.3	0.128	0.073	0.38	43.0	3.04	43
4.4	54.0	7.6	11.8	0.135	0.081	0.44	44.0	3.20	40
5.4	66.2	7.5	12.2	0.141	0.085	0.54	44.5	3.22	40
Average		7.3	12.2	0.136	0.086	..	41.5	2.83	37

Series 5—Gas velocity 400 c.f.m.—Water circulation 147 g.p.m. Time of contact—5.1 sec.

1.2	30.0	3.4	16.8	0.084	0.025	0.23	33.5	3.12	48
2.8	68.0	4.0	15.9	0.075	0.062	0.35	37.5	1.08	17
3.2	76.0	3.1	17.0	0.063	0.027	0.43	38.0	2.85	57
4.2	102.0	3.9	16.2	0.081	0.036	0.52	39.0	3.78	56
5.2	126.0	3.6	16.4	0.077	0.040	0.63	40.0	3.11	48
7.2	174.0	3.8	16.6	0.084	0.053	0.85	38.5	2.57	37
8.2	198.0	3.0	17.4	0.066	0.027	0.95	37.8	2.96	59
9.2	222.0	3.7	16.7	0.100	0.060	1.07	37.5	3.29	40
12.2	294.0	3.9	16.5	0.102	0.071	..	37.5	2.62	30
13.2	318.0	3.1	17.1	0.069	0.034	1.50	38.0	2.85	51
14.2	342.0	3.2	16.7	0.096	0.058	..	38.0	3.19	40
16.2	390.0	4.2	15.8	0.130	0.092	..	40.0	3.42	30
21.2	510.0	4.3	15.7	0.095	0.075	1.90	40.0	1.81	22
Average		3.6	16.5	0.087	0.051	..	38.2	2.82	41

Series 6—Gas velocity 101 c.f.m.—Water circulation 14.5 g.p.m. Catalyst concentration—125 p.p.m. manganese. Time of contact—20.0 sec.

1.2	7.1	6.2	13.7	0.137	0.033	0.18	27.5	2.35	76
2.2	13.2	6.0	13.8	0.130	0.042	0.23	32.0	2.12	68
3.2	19.2	6.0	13.9	0.118	0.040	0.33	35.0	1.87	66
4.2	25.3	6.5	13.6	0.144	0.059	0.39	36.5	2.12	59
5.2	31.4	6.0	13.3	0.177	0.088	0.46	38.0	2.27	50
7.2	43.5	7.0	12.0	0.169	0.093	0.60	41.5	2.21	45
8.2	49.6	7.3	12.1	0.183	0.106	0.66	42.0	2.23	42
9.2	55.7	7.0	12.7	0.164	0.090	0.71	43.0	2.12	45
10.2	60.7	7.0	12.6	0.146	0.074	0.76	43.0	2.02	49
11.2	67.8	7.0	12.6	0.198	0.117	0.82	44.0	2.31	41
12.2	73.9	7.1	12.2	0.189	0.109	0.88	44.0	2.34	42
13.2	80.0	7.0	12.7	0.140	0.073	..	44.0	1.87	48
Average		6.7	12.8	0.158	0.077	..	36.6	2.15	51

Series 7—Gas velocity 102 c.f.m.—Water circulation 15.2 g.p.m. Catalyst concentration—500 p.p.m. manganese. Time of contact—20.0 sec.

1.1	6.6	7.4	12.4	0.215	0.048	0.28	28.0	4.40	78
2.1	12.7	8.0	11.4	0.195	0.061	0.39	33.0	3.95	69
2.9	17.8	7.9	11.4	0.167	0.053	0.46	35.0	3.39	68
4.1	25.0	7.2	12.5	0.137	0.053	0.57	39.0	2.33	61
5.0	30.6	7.2	12.6	0.132	0.046	0.63	41.0	2.39	65
6.0	36.7	7.4	12.3	0.126	0.043	0.72	41.0	2.50	66
6.9	42.3	7.1	12.5	0.131	0.041	0.78	42.0	2.56	69
8.9	54.5	6.5	12.8	0.131	0.047	0.90	43.5	2.36	64
9.9	60.7	6.8	12.7	0.123	0.048	0.98	43.5	2.13	61
10.9	66.8	7.9	11.6	0.127	0.055	1.04	46.3	2.27	57
11.9	72.9	7.1	12.6	0.130	0.056	1.14	44.3	2.13	57
12.9	79.0	7.0	12.3	0.130	0.062	1.28	44.3	2.01	52
13.9	85.1	6.4	12.8	0.124	0.048	1.43	44.0	2.18	61
14.9	91.2	6.8	13.0	0.113	0.043	..	43.8	1.95	62
15.9	97.5	6.6	13.0	0.128	0.058	1.56	43.8	1.95	55
16.9	103.0	6.2	13.8	0.118	0.045	..	43.0	1.91	62
17.9	110.0	6.4	13.4	0.090	0.037	1.76	43.5	1.46	59
18.9	116.0	6.2	13.8	0.095	0.032	..	42.0	1.67	66
19.9	122.0	5.6	14.2	0.095	0.028	1.91	41.5	1.72	71
20.9	128.0	6.3	13.6	0.100	0.036	..	41.5	1.72	64
21.9	134.0	6.0	14.0	0.105	0.027	2.00	41.0	2.06	74
22.9	140.0	5.9	14.0	0.125	0.048	..	41.0	2.03	62
23.9	146.0	5.3	14.2	0.128	0.047	2.02	41.0	2.10	63
24.9	152.0	6.7	12.9	0.188	0.113	..	41.0	2.14	63
Average		6.5	12.9	0.131	0.049	..	41.2	2.39	63

Required Contact for Absorbing Oxygen

In absorbing oxygen from flue gases the conditions are quite different from those affecting the absorption of sulphur dioxide by untreated water. In the first place, the quantity of oxygen required seldom exceeds 0.2 per cent by volume of the gases, and, since the gases contain from 5 to 12 per cent, the oxygen concentration remains essentially constant throughout the washer. Furthermore, at sufficient catalyst concentration, the dissolved oxygen is removed as fast as it is absorbed. The conditions, therefore, are ideal for rapid absorption, which will be determined only by the solubility and the resistance of the liquid film.

The solubility of oxygen follows Henry's law, i.e., it is proportional to the partial pressure of the oxygen in the gases. At 25 cent. (77 fahr.), the solubility, C_0, expressed in pounds per pound of water, is

$$C_0 = 40.3 \times 10^{-8} b \qquad (3)$$

where b is the percentage of oxygen in the gases; the gases are considered under atmospheric pressure.

The rate of absorption in pounds per hour, therefore, is

$$\frac{W_0}{\Theta} = A k_L C_0 \qquad (4)$$

where k_L is the liquid film coefficient in pounds per square foot per hour per unit concentration,

A is the absorption area, square feet

Since both k_L and C_0 are functions of temperature and of acid concentration, it is necessary to make corrections for these.

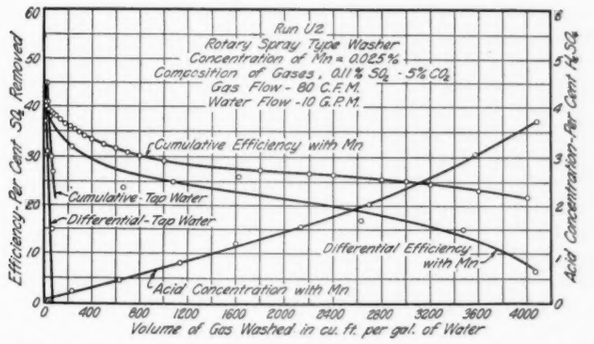

Fig. 9—Efficiency of rotary spray washer on flue gases using catalyst solution.

The curves in Fig. 6 show the relative rates of absorption at various temperatures and concentrations of acid. Those for temperature are calculated from solubility data, partial pressure of oxygen above water, and the formula of Haslam, Hershey and Keen (*14*) for the liquid film coefficient,

$$k_L \propto T^4,$$

where T is the absolute temperature (deg. cent. + 273). The curves for acid concentration are calculated from Geffchen's data on solubility of oxygen in sulphuric acid solutions (*15*) at 25 cent., and are corrected for viscosity and density according to Haslam's other formula:

$$k_L \propto (S/Z)^{2/3}$$

where S is the density of the liquid, and
Z is the viscosity of the liquid.

Use of the two curves together should give an approximation to the rate of absorption of oxygen by sulphuric acid solutions at any temperature. The corrected rate of absorption is

$$\frac{W_0}{\Theta} = 40.3 \times 10^{-8}\, A \cdot k_3\, k_4\, k_L\, b \qquad (5)$$

where k_3 and k_4 are the temperature and acid corrections, respectively. The coefficient, k_3, contains the moisture correction to the percentage of oxygen which is ordinarily determined by Orsat, and, thus is for dry gases.

Experimental—Packed Tower Washer

The application of the catalytic oxidation system to flue gases has been studied with the three types of washers. Of these, the tests made with the packed tower were on the largest scale. The equipment used, as shown in Figs. 7 and 8, consists of a 42-in. stoneware tower packed for a height of 5.5 ft. with 3 × 3-in. spiral packing. The water containing the catalyst was circulated over the packing and returned by means of an air-lift to an electrolysis box, from which it flowed to a storage tank.

The tower had a small ratio of height to cross-sectional area in order to reduce the draft loss to a point compatible with operation on a large scale. In order to avoid channeling of the water over the packing a perforated distributor plate was used and the water velocity was maintained at the high rate of 16 gal. per min. While the actual ratio of gas to water in the tower was necessarily small due to the dimensions of the tower, it is felt that the capacity of the liquid is indicated by the total volume of gas washed with a given amount of liquid rather than by this ratio. The reason for this is that, as long as oxidation takes place faster than oxygen absorption, the problem is one of absorbing a given weight of a gas from an essentially constant gas composition. The driving force of absorption remains constant, therefore, throughout the run except for the effect of temperature and acidity. The results of an entire run represent the conditions at points from top to bottom of a large counter-flow washer in which the ratio of gas to liquid is that of the total volume of gas washed to the starting volume of water.

The normal constants of the packing used showed 29 sq. ft. per cu. ft. of tower space and 64 per cent free space.

Complete arrangements were made for metering the gas and liquor and for analysis for sulphur dioxide, carbon dioxide and oxygen before and after washing and at every foot of tower height.

The results of a series of runs made at different gas velocities, and with different catalyst concentrations for a constant gas velocity, are shown in Table VI. In all cases the starting volume of water was 400 gal. In column 9 the ratio of the weight of sulphur dioxide absorbed, in pounds per hour, to the corrected solubility of oxygen is shown. If the removal of the gas depends on the rate of absorption of the oxygen, according to Equation 5 this ratio should be constant ($W_s = 4W_0$). Actually considerable variation is shown. Whether this is due to errors in analysis, or whether the variation is significant cannot be stated. A peculiar characteristic of the oxidation method has always been noted in the sensitiveness of the results to slight variations in the nature of the flue gases, especially in regard to the soot content. This was so true that the bubble washer was completely useless when operating on flue gases. These results are discussed below.

Spray Washer

In some preliminary work a small single-effect rotary scrubber was used having a capacity of 100 cu. ft. of gas per min. The water containing the catalyst was circulated through the washer at the rate of 8 gal. per min. Since it is impossible to estimate the time or surface of contact in this washer, the data are not tabulated here but are shown in Fig. 9. The curves show the great increase in the capacity of the water for absorbing sulphur dioxide in the presence of the catalyst but indicate that the rate of absorption is not increased by the oxidation.

Bubble Washer

A large number of tests were made on flue gases with the bubble washer under conditions similar to those used for the air-sulphur dioxide mixtures. The results, of which Fig. 10 is an example, showed that for both catalysts, iron and manganese salts, the contact of 2 seconds, or 1180 sq. ft. seconds per cu. ft. of gas, was sufficient to remove all of the sulphur dioxide at the start of the run. The dissolved gas was completely oxidized by the oxygen. The oxygen content of the gases during these tests averaged approximately 14 per cent and, therefore, the efficiency was not affected by lack of this gas.

Inhibitors

The possibilities of the use of the catalytic oxidation system were considerably lessened by the results with the bubble washer. In every case, the high efficiency abruptly fell to practically zero on account of a termination of the catalytic action. This poisoning of the catalyst took place at various intervals ranging from 50 cu. ft. per gal. of water to 800 cu. ft. Apparently, the poisoning was more rapid in the bubble washer than in the packed tower, and was least in the spray washer.

A complete investigation of the source, the effect and possible ways of removing these reaction inhibitors was made in the course of the research. The results indicate that the action is due, at least in part, to the absorption of phenolic compounds present in the gases and the soot, as a result of incomplete combustion of the coal. Also, some of the inorganic constituents of the ash are capable of effecting the same results. In the laboratory, a number of substances were tested for inhibitory power and as a result two classes were established: (1) compounds for which the action is permanent

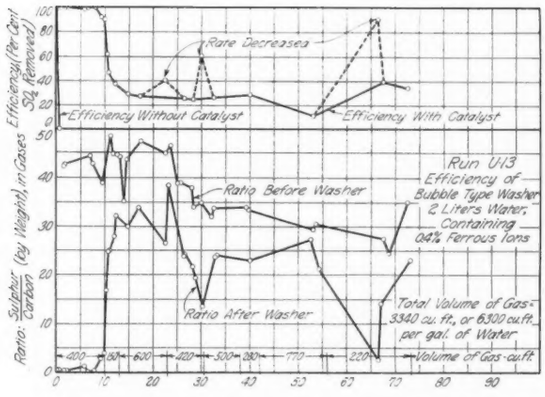

Fig. 10—Efficiency of bubble washer on flue gases using catalyst solution.

and proportional to the total amount added, (2) compounds for which the action is temporary and which are slowly removed as a result of oxidation. Of the former, phenols and copper salts are the most important and powerful, as little as one-tenth part per million showing a considerable effect on the rate of oxidation. The phenols, of course, are present in traces in all flue gases, while the action of copper salts prohibits the use of brass fittings in the washer construction. Of the temporary inhibitors, tin salts are an example.

These inhibitors are more active in the case of manganese, but the catalysis by iron salts is noticeably affected by small concentrations of the phenols. In order to prove the existence of the phenolic inhibitors in flue gases, the solution from the bubble washer was analyzed for this constituent and, in every case, was found to contain from 0.1 to 1 part per million. In some cases, for instance, with the tower washer, the presence of phenols was not sufficient to explain the entire effect so that other adverse compounds were evidently being absorbed. The results reported for the tower washer are all for the part of the run before the inhibitor action set in, so that they represent the true rate of absorption for the oxidation system. It was an easy matter always to tell when the solution was inhibited both by the odor of sulphur dioxide in the effluent water and by the sudden dropping of the efficiency. In no case was it possible to attain an acid concentration from the flue gases above 4 per cent, and in some cases only 1 per cent was reached.

A few possible ways for removing the inhibitors were studied. For the most part these are not economically satisfactory. The phenol concentration in the water could be kept down by circulating the water through activated charcoal, but this procedure did not remove other inhibitors. In the laboratory it was found possible to remove the action of all the inhibitors studied by passing a small electrolyzing current through the solution, using lead electrodes. A minimum current density

TABLE VII—REQUIRED CONTACT SURFACE FOR ABSORBING OXYGEN REQUIRED TO OXIDIZE SULPHUR DIOXIDE

Square feet × seconds per cubic foot of gas

Gas	Surface: Bubble Small[16]	Bubble Large[17]	Packed Tower†	Spray[18]	Stationary[19]
			By Water		
Air—0.325% SO_2	374	550	1965	12,000	292,000
12% O_2—0.15% SO_2	310	445	1590	9,690	236,000
7% O_2—0.325% SO_2	1120	1650	5920	36,000	876,000
			By 21% Sulphuric Acid Solution		
Air—0.325% SO_2	593	872	3120	19,000	472,000
12% O_2—0.15% SO_2	498	702	2520	15,340	382,000
7% O_2—0.325% SO_2	1775	2610	9370	57,000	1,416,000

[16] From coefficient, k_L = 178 lb. per hr. per sq. ft. per lb. per lb. concentration difference, estimated from data for small bubbles of volume 0.036 cc. Ledig and Weaver, *J. Am. Chem. Soc.*, Vol. 46, p. 654, 1924.

[17] From coefficient, k_L = 121, estimated from data for average absorption rate by cylindrical bubbles 5 cc. in volume, 1.06 cm. in diameter and 5.9 cm. in length. Adeney and Becker, *Philosophical Mag.*, Vol. 39, p. 385, 1920.

† From coefficient, k_L = 33.9, the value calculated from the average rate of absorption in Table VI.

[18] From coefficient, k_L = 5.58, for liquid stirred at 60 r.p.m. Becker, *Ind. Eng. Chem.*, Vol. 16, p. 1222, 1924.

[19] From coefficient, k_L = 0.22 for liquid at rest. Becker, *loc. cit.*

is required to overcome the action, depending on the character and concentration of the inhibitor. Thus, hydroquinone, the strongest inhibitor studied, when present to the extent of 1 part per million, could be removed by a current of 2 amperes on 12 sq. in. if the current was flowing when the inhibitor was added and continued for 20 sec. after the addition. Aeration in addition to the electrolysis was found to promote the removal.

In the experiments with the tower washer, the water was returned to an aeration box arranged with lead electrodes and a current of 7 amperes on 100 sq. in. was applied. While some benefit was apparent, the accumulation of the catalyst poison could not be prevented for a period of more than 40 hours.

Conclusions Regarding Oxidation Methods

As a result of this research on the oxidation system, we conclude that it has only a limited application to the removal of sulphur dioxide from flue gases. The two outstanding

TABLE VIII—ABSORPTION OF SULPHUR DIOXIDE BY ALKALINE SOLUTION (SODIUM CARBONATE) IN PACKED TOWER WASHER

Water circulation—16 g.p.m.

Gas Velocity, Cu. Ft. per Min.	Sampling Point, Ft. of Packing	Time of Contact at Sampling Point, Sec.	% SO_2 Entering	% SO_2 at Sampling Point	% CO_2 Entering	% Removal
460	5.5	4.4	0.132	0.024	7.0	82
460	5.5	4.4	0.151	0.008	9.3	95
460	5.5	4.4	0.128	0.007	9.2	95
460	2.0	1.6	0.142	0.004	...	97
460	2.0	1.6	0.153	0.006	...	96
462	2.0	1.6	0.149	0.003	7.1	98
462	1.0	0.8	0.147	0.009	...	94
462	1.0	0.8	0.138	0.013	...	91
462	1.0	0.8	0.126	0.021	...	84
1012	5.5	2.0	0.163	0.003	7.3	98
1012	5.5	2.0	0.102	0.008	...	92
1012	5.5	2.0	0.157	0.010	7.2	94
1012	2.0	0.73	0.165	0.014	...	92
1012	2.0	0.73	0.159	0.013	...	92
1012	1.0	0.36	0.152	0.057	...	63
1023	2.0	0.72	0.055	0.008	...	85

difficulties are the slow rate of absorption of oxygen and the accumulation of catalyst poisons in the solution. On account of the latter, it is impossible to attain a concentration of sulphuric acid of any commercial value when the gases from the combustion of coal are treated. For many plants this means that a method of disposal of the dilute acid must be found, as contamination of surface waters by the large amount of sulphuric acid would not be tolerated.

Even with the accumulation of one per cent sulphuric acid, the method has the one advantage of greatly increasing the capacity of the water for absorbing sulphur dioxide, and thus reducing the quantity of water required to wash a given volume of gas as compared to that of untreated water. Because of the limitation, however, the cost of manganese salts would be prohibitive, but scrap iron may be used, as in the plans of the London Power Company.

For spray and wetted-wall washers, which are available for washing flue gases, the oxidation method in no way reduces

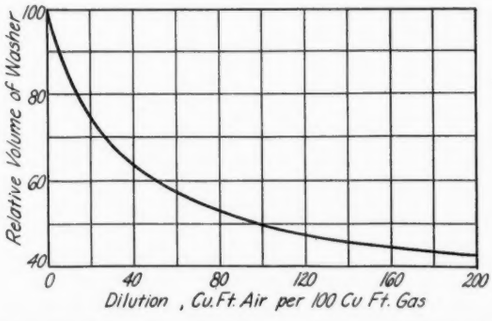

Fig. 11—Calculated effect of dilution of waste gases with air on washer size when oxidation system is used. Basis: Gases at 300 fahr., containing 8 per cent O_2.

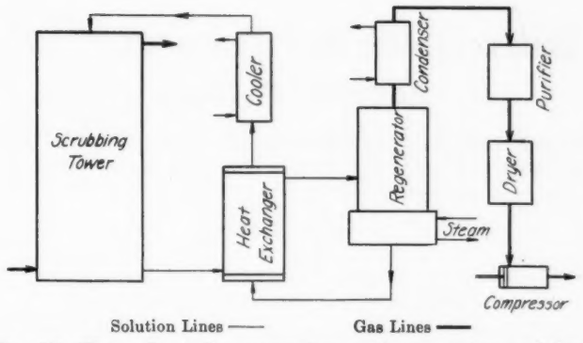

Fig. 12—Flow sheet for removing and recovering sulphur dioxide from waste gases.

the time of contact required for absorbing the sulphur dioxide. For bubble washers, however, in which the absorption of oxygen is rapid, the contact is greatly reduced. A comparison of the contact required for absorbing the necessary oxygen from various gases is shown in Table VII. These figures should be compared with those in Table II. The values are calculated on the assumption that the oxygen reacts with the sulphur dioxide as fast as it (the oxygen) dissolves and that the presence of the sulphur dioxide does not influence the rate of oxygen absorption. The latter possibility is being investigated because of its theoretical and practical importance. The film coefficients used are indicated in the footnotes.

A very interesting possibility appears on the basis of the assumptions made in the previous paragraph, in connection with the effect of dilution of the waste gases with air. If the rate of absorption is proportional to the concentration of oxygen in the gases, then the contact required for a given gas, in square feet seconds per cubic foot, is directly proportional to the concentration of sulphur dioxide in the gases, and inversely proportional to the concentration of oxygen. Accordingly, dilution of any gas, containing less than 20 per cent oxygen, with air will decrease the contact required. The effect depends on the percentage of oxygen and is surprisingly large for gases containing as little as 8 per cent O_2. The curve in Fig. 11 shows the calculated effect on the washer size when gases at 300 fahr. containing 8 per cent O_2 are diluted with air. There is of course a limit to the effective dilution which is reached when the sulphur dioxide is absorbed as slowly as the oxygen.

Application to Other Industries

Because of the great increase in the capacity of the wash water and the faster rate of absorption when bubble washers are used, as shown in Table V, the oxidation method seems to be available for the removal of sulphur dioxide from other waste gases where the purity of the gases and the small volume will permit its use. In these cases the power requirements to overcome the several inches of water draft loss in the bubble washer will not be great. Some development has been reported on the use of the method in the sulphuric acid industry for the removal of the sulphur dioxide in the waste gases from the contact process.

Of particular interest is the recent paper by Copson and Payne (*20*) on the application to waste gases from petroleum refineries where the sulphur dioxide varies from 0.6 to 12 per cent. In this case no inhibitory action was found in impurities in the gas. Absorption rates in a bubble washer were found as high as 20 grams per hour per liter of active volume (1.25 lb. per hr. per cu. ft.) by 20 per cent sulphuric acid, and 32 grams per hour per liter, initially by water.

Use of Alkaline Agents for Washing Gases

The high rate of absorption of sulphur dioxide by alkaline solutions makes these reagents attractive for removing the sulphur compounds from flue gases. At the Battersea Station their use was planned for removing the last traces of sulphur dioxide. In a test made on the packed tower washer described above a solution of sodium carbonate (soda ash) was used. The results, shown in Table VIII, indicate that the rate of absorption is approximately 50 times that when the oxidation system was used. Similar results were obtained when a lime suspension was circulated.

The capacity of the wash liquor when an alkali is used is, of course, proportional to the amount of the chemical added. In the case of lime (as $Ca(OH)_2$) the weight of sulphur dioxide absorbed is 86.5 per cent of the weight of the lime, plus the normal solubility of the sulphur dioxide in water. For a coal containing 3 per cent sulphur, the amount of lime required per ton of coal would be approximately 140 lb., for which the cost could seldom be justified.

Another possibility exists in the use of alkaline solutions, however, in which the high rate of absorption is retained while the cost is reduced. This is the procedure of regenerating the absorbing agent by heating. A number of such processes have been used to advantage in the chemical industry, but little success has been had with the recovery of sulphur dioxide. In studying the properties of certain ammonium salt solutions, it was found that they were quite alkaline at ordinary temperatures and only slightly so at temperatures near the boiling point. These are capable of absorbing large quantities of sulphur dioxide when cold and give up at least a part of this when heated. Several of the cheapest of these reagents have been used in this way on flue gases and have shown capacities for absorbing sulphur dioxide up to 6 per cent by weight of the solution with the absorption temperature at 80 fahr. and the regeneration temperature at 200 fahr. A flow sheet of the process used is shown in Fig. 12.

It is impossible at the present time to predict the possibilities of this method until a complete study of equilibrium conditions is finished. The method is attractive because it yields as a by-product sulphur dioxide of such concentration and purity that it should find a ready market. At the present time the price of sulphur dioxide on the New York market makes the sulphur in a ton of 3 per cent sulphur coal worth 84 cents, a considerable margin for the extraction from flue gases. Furthermore, the depletion of the known reserves of sulphur in this country makes it all the more desirable to conserve the natural resources (*21*).

Further reports on this development will be made when results justify them.

Summary

This paper discusses the problem of the elimination of sulphur dioxide from waste gases from the chemical engineering standpoint. It is shown that the possibility of economically washing large quantities of gases, such as those from central power station boilers, is very remote. The limits imposed by the solubility of sulphur dioxide from such dilute gases are those of the quantity of water required and the time and surface of contact needed. The several types of washers are compared and, of these, the bubble type is found to require the least time of contact and smallest volume of washing space. The approximate size of a spray washer for removing the sulphur dioxide from one million cubic feet per minute of gas containing 0.3 per cent sulphur dioxide, is 860,000 cu. ft.

A comprehensive study has been made of the catalytic oxidation method for removing sulphur dioxide. For pure gases this method has the advantage of requiring only approximately one per cent of the water required for simple absorption. A by-product of sulphuric acid containing up to 40 per cent acid may also be produced. The time of contact, however, for spray and packed tower washers is not reduced. For flue gases from the combustion of coal, impurities render the catalysts inactive and not more than 4 per cent acid may be produced. The method is available for washing small quantities of pure gases containing up to 12 per cent sulphur dioxide and for which a bubble type washer may be used.

Development of a regenerative system for recovering sulphur dioxide using alkaline reagents has been started. The results are attractive both from an engineering and an economic viewpoint.

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Obituary

R. H. Barber died on July 12 at Hull, Province of Quebec, as the result of an automobile accident. Mr. Barber was Superintendent of Steam Plants for the International Paper Company, which position he has occupied for the past 8 years. For about 15 years prior to that he was Chief Engineer of the New Bedford Gas & Edison Light Company. He was one of the early members of the Prime Movers Committee of the National Electric Light Association and was widely known as an authority on steam plant design and operation. Mr. Barber's funeral took place on July 15 from his home at White Plains, N. Y.

The Coppus Engineering Corporation, Worcester, Mass., announces the appointment of the Blower Application Co., 918 North Fourth St., Milwaukee, to handle its line of Annis Industrial and Ventilating Filters in the state of Wisconsin, excluding Florence and Marinette counties.

Boiler, Stoker and Pulverized Fuel Equipment Sales

As reported by equipment manufacturers of the Department of Commerce, Bureau of the Census.

Boiler Sales

Orders for 326 water tube and h.r.t. boilers were placed in March, April, May and June.

	Number	Square Feet
March, 1933	55	170,898
April, 1933	66	150,949
May, 1933	84	267,093
June, 1933	121	361,034
January to June (inclusive, 1933)	383	1,146,250
Same period, 1932	311	1,012,639

NEW ORDERS, BY KIND, PLACED IN MARCH, APRIL, MAY & JUNE

	March, 1933		April, 1933		May, 1933		June, 1933	
Kind	No.	Sq. Ft.	No.	Sq. Ft.	No.	Sq. Ft.	No.	Sq. Ft.
Stationary:								
Water tube	40	151,580	34	112,394	51	222,373	73	300,352
Horizontal return tubular	15	19,318	32	38,555	33	44,720	48	60,682
	55	170,898	66	150,949	84	267,093	121	361,034

Mechanical Stoker Sales

Orders for 421 stokers, Class 4,* totaling 86,084 hp. were placed in March, April, May and June by 42 manufacturers.

	Installed under			
	Fire-tube Boilers		Water-tube Boilers	
	No.	Horsepower	No.	Horsepower
March, 1933	67	8,794	17	7,756
April, 1933	26	3,370	31	10,229
May, 1933	52	7,495	41	15,717
June, 1933	137	16,523	50	16,200
January to June (inclusive, 1933)	365	48,277	174	61,168
Same period, 1932	379	50,963	185	77,816

* Capacity over 300 lb. of coal per hr.

Pulverized Fuel Equipment Sales

Orders for 28 pulverizers with a total capacity of 86,190 lb. per hr. were placed in March, April, May and June.

STORAGE SYSTEM

	Pulverizers				Water-tube Boilers		
	Total Number	No. for new boilers, furnaces and kilns	No. for existing boilers	Total capacity lb. coal per hour for contract	Number	Total sq. ft. steam-generating surface	Total lb. steam per hour equivalent
March, 1933	..	..	..	.....	..	.....	.....
April, 1933	..	..	..	.....	..	.....	.....
May, 1933	..	..	..	.....	..	.....	.....
June, 1933	..	..	..	.....	..	.....	.....
January to June (inclusive, 1933)	2	..	2	60,000	2	37,000	325,000
Same period, 1932	..	..	..	.....	..	.....	.....

DIRECT FIRED OR UNIT SYSTEM

	Pulverizers				Water-tube Boilers		
March, 1933	5	2	3	12,150	4	20,334	130,200
April, 1933	3	1	2	9,500	3	12,690	111,600
May, 1933	3	2	1	7,500	2	5,600	42,800
June, 1933	11	7	4	52,090	11	63,415	501,420
January to June (inclusive, 1933)	34	23	11	160,240	27	174,673	1,483,360
Same period, 1932	40	27	13	207,338	36	199,086	1,868,450
					Fire-tube Boilers		
March, 1933	1	..	1	1,200	1	1,150	8,000
April, 1933	..	..	..	.....	..	.....	.....
May, 1933	1	..	1	750	1	1,500	7,800
June, 1933	4	..	4	3,000	5	7,500	30,800
January to June (inclusive, 1933)	9	2	7	7,700	10	14,150	64,900
Same period, 1932	12	1	11	12,300	12	19,000	108,750

Standby and Reserve Operation of a Pulverized Fuel Plant[1]

By E. H. TENNEY[2]

The growing necessity for greater load pick-up ability in steam-electric generating plants has increased the importance to plant operators of standby and reserve operation, which brings up some of the most difficult operating problems an operator must face. Interconnection of Cahokia Station with two distant hydro plants required a study of all of the system's governors for those characteristics which determine load distribution in time of system fault. After determining the severest reserve condition that had to be met, boiler room personnel was organized to be able to meet a load increasing from 18,000 kw. to 63,000 kw. almost instantly. This required a study of pulverized fuel firing for minimum steam output and maximum rate of increasing steam output.

POWER plant operators have realized the necessity for keeping reserve equipment in readiness to carry plant load in case some part of the operating equipment stops functioning. In the same way plants stand ready to assist one another to maintain service in interconnected power systems. The latter type of reserve (one plant picking up the load lost by another) brings up some of the most difficult problems that an operator has to face, particularly in the boiler room. Trouble, usually of an electrical nature, can throw the load of one plant onto another almost instantaneously and increase the latter's demand for steam by as much as several hundred per cent. Every phase of combustion and boiler operation is involved in meeting this situation.

Several developments in recent years have combined to make standby or reserve operation a more frequent problem in steam plants. Generating stations are becoming more and more widely interconnected which permits very efficient plants to be operated at close to capacity and the less efficient plants at very low load. The less efficient plant must then stand by for the heavily loaded, efficient plant. The economic situation has left most electric systems in this country over-supplied with generating capacity. Substantial operating economies can be effected by virtually closing down plants of intermediate economy except as standby. The growing tendency to more thoroughly interconnect hydro with steam plants leaves the latter as standby during seasons of plentiful water supply. Finally the elaboration of quick response electric controls and the higher standards for continuity of electric service have so advanced that boiler rooms are being called upon to meet rapid and large increases in steam output. To meet this requirement for reserve without extravagance and to develop further boiler flexibility for still greater system economies, requires careful choice of firing equipment, a detailed knowledge of what takes place in the turbines and boilers at times of system fault, and a thoroughly organized schedule of operation.

A review of the recognized power plant practice in carrying reserve would be of great value but it would be decidedly lengthy, and it is intended here to discuss the methods followed in only one pulverized fuel plant, the Cahokia steam power plant of the Union Electric Light & Power system. The general procedure to be described, however, has been compared with practice elsewhere and it is believed that it is sufficiently typical to be of some interest.

In this discussion both standby and reserve are taken to mean ability to pick up load instantly. Keeping a steam plant hot in order to pick up load *on notice* is a very different problem. The problem of *immediate* reserve can be divided into the several phases in which a sudden load increase affects plant performance:

(1) The rapidity and extent to which turbines pick up load in response to a system fault and the drop in frequency incident thereto.

(2) The time and rate at which greater turbine load results in demand for greater steam plant output.

(3) The result on boilers and boiler steam pressure as the increase in steam demand reaches the boiler room.

(4) The rate at which fuel burning can be stepped up to meet the demand for steam and avert excessive drop in steam pressure.

Turbine Performance

In the final analysis the ability of a plant to pick up load depends upon the boiler room. The conditions to be met, however, are imposed by the turbines which in turn are controlled by their governing mechanisms. While it is not necessary to review governor performance as thoroughly as it is considered by the designer, some knowledge of the process by which the governors transfer a system fault and frequency drop to the steam admission valves of the turbine will assist the operator in developing a proper boiler room set-up.

Turbines of central stations, being electrically interlocked by the system frequency, operate at a speed determined by that frequency. The governors act primarily then in determining a prime mover's load. When the loss of generating capacity occurs in the system the remaining prime movers on load are temporarily overloaded, they slow down, and the system frequency drops. Unless the prime movers are actuated by quick acting frequency relays to open the throttle (a method of control not generally used as yet) it remains for the governors of all turbines on load to open their respective steam admission valves in an effort to restore the system frequency. The drop in speed through which they are slowed down by the additional load is determined by many factors, including the fly wheel effect of the system's rotating prime movers, the sensitivity of the governors, the governor time lag, and the rate at which the units pick up load for a given frequency drop. In practice the process of load change is not instantaneous and there is usually time, before conditions become settled again, for operators to manually assist in the new load distribution.

It is not possible to assume that during a system fault the load will automatically redistribute itself in proportion to the amount of reserve capacity each plant is carrying. The

[1] Presented by the Fuels Division of the A.S.M.E. at the semi-annual meeting of the Society, Chicago, June 25–July 1, 1933.

[2] Chief Engineer of Power Plants, Union Electric Light & Power Company.

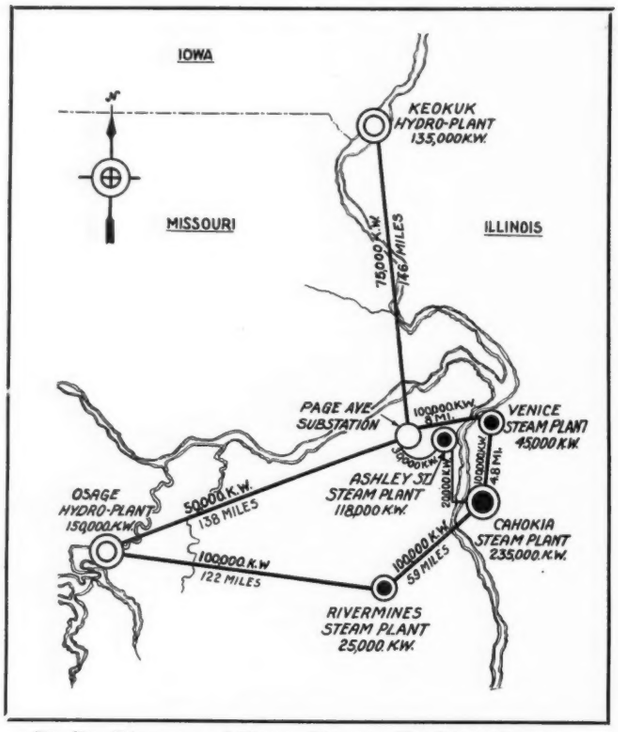

Fig. 1—Diagram of Union Electric Tri-State System.

governors of steam turbines are, as a rule, sufficiently responsive to automatically divide load among the generators on the line according to their regulation characteristics. If there is a hydro plant on the system, however, with relatively insensitive and sluggish governors then the steam plants will obviously absorb practically all the load increase at times of system fault, and, unless these conditions are known and allowed for, an overloaded boiler room and disappearing steam pressure may result.

As a guide to what a study of system governors may include a brief review of an actual study will be made here, and the method used for determining what was considered the pertinent governor characteristics will be described.

Briefly the governors were analyzed for four characteristics: speed regulation (or inherent speed droop), sensitivity, time lag and rate of load pick-up.

1. The *speed regulation* (or inherent speed droop) was considered as the per cent of decrease of change in normal rated speed which will automatically increase turbine output from no load to full load. A representative regulation is 3.5 per cent, which on a 60-cycle turbine means approximately that a machine carrying no load will automatically increase to full load if the frequency drops to 57.9 cycle.

2. *Sensitivity* was considered as the number of cycles in frequency change required to cause a governor to initiate a valve opening.

3. *Time lag* is the time interval between a change in system frequency and the governor's response.

4. *Responsiveness* is a term used in this study to cover the rate at which a turbine actually picks up load in time of system fault and is largely the resultant of the first three characteristics. It is expressed as a figure which is the product of the number of cycles change in speed multiplied by the number of seconds required for the unit to increase from no load to full load with that frequency change.

Governor Tests

The surest test to determine how load would be divided among the plants of a system would require actually tripping units off the load, but this is not often feasible. In the study here described the compromise used was (1) observation of what happened on the other units of the system when certain generators were rapidly unloaded by hand, (2) study of separate governors while they regulated their units during normal operation. The system tested is that shown in Fig. 1. Only three of the plants were generating at the time, two hydro plants, Keokuk and Osage, and Cahokia, a steam plant. Some of the results of the study are briefly summarized in Table I.

TABLE I—COMPARATIVE GOVERNOR PERFORMANCE

	Steam Plant Unit No. 1	Steam Plant Unit No. 2	Typical Hydro Plant
Sensitivity (cycles)	0.02	0.03	0.06
Time lag (seconds)	1	1	2
Regulation (speed drop in per cent of full load)	2.8	5.1	3.1
Responsiveness*	12	15	27

* Product of time in seconds to pick up full load from a closed position × the frequency drop in cycles.

In the first type of test, load was manually taken from one group of units, while others were free to follow their governors. A series of such tests with the load swing being handled on various units indicated the relative responsiveness of the system's governors as they affect load distribution under fault.

A recently developed instrument that greatly aided the study of governor characteristics is a highly sensitive frequency recorder of a galvanometer type virtually without lag. This instrument with a rapidly moving strip chart can be attached to the frequency while another pen records the mechanical motion of the governor steam valve actuating rod. The time lag and sensitivity of a governor can be almost instantly observed by comparing governor response to frequency change, Fig. 2.

Such a study of governor characteristics, while of great assistance in estimating the change in steam demand which a boiler room must meet, can be used only as an *indication* of what the load distribution will be in a system fault. Its chief value is to discover governor differences in the system and to determine if a relayed load will fall on the plant where reserve is being carried. It may be desirable to have each of several plants assume its portion of a load transfer, in which case a governor study will indicate where improvements in governor responsiveness are needed.

If it is not possible to adjust or install governors of the relative responsiveness desired then it is necessary that system reserve be set up where there is sufficient generator capacity to handle it and rely on the manual control of switchboard operators to get the distribution of loading wanted. A few seconds after a fault the load will automatically divide according to the sensitivity and responsiveness of governors with the result that some generators and plants will be loaded beyond their rating. Quick action on the part of the switchboard operators is then necessary to manually depress the governor synchronizing springs so that a given unit or plant is carrying no more load than it can handle. If left to itself, of course, the load will, in a matter of several minutes, redistribute itself according to the inherent speed droop characteristics of the governors. The other governor characteristics, such as sensitivity and time lag, enter into the change only during the first fraction of a minute.

Boiler Performance

The sudden load increase which has fallen on a standby plant first increases the generator output. Then by the time the governor has acted and the turbine steam admission valves opened the turbine also has met the increased load. This increases the flow of steam, which increase is initially met by the steam storage capacity of the boiler, a portion of the high temperature water flashing into steam while the boiler pressure drops. Finally furnace firing and boiler steaming rates are increased by the operators as rapidly as possible so as to stop the drop in boiler pressure and then bring it back to normal. The entire cycle from the time of the system fault to the time the boiler steam pressure is kept from falling further is usually less than three minutes.

The ability of a boiler room to meet a fault condition depends upon several factors, some mechanical and some human:

(1) The ratio of the steam demand increase to the load already being carried—up to 25 per cent increase in steam demand being a fairly simple problem.

(2) The time required to inform the boiler house crews of the situation.

(3) The effectiveness of boiler house organization for coping with rapid increases in steam output.

(4) The mechanical limitation of the boilers in respect to steam release and water storage.

(5) The rapidity with which increasing quantities of coal and air can be delivered to the furnace in combustible condition.

The difficulty of the problem of standby depends upon the amount of reserve in kilowatts or per cent of load for which the plant is standing by. In some electrical generating systems each prime mover or plant is operated at the point of its best efficiency, the system swing being taken on the least efficient unit. When this is the case the primary consideration is not one of system economy, for such load distribution seldom gives the best overall economy. Best economy is almost always obtained by carrying nearly full rating on the newest and best equipment with low loads on the older units of comparative inefficiency. With this latter type of loading the problem of reserve is much more difficult because usually the bulk of the system reserve is carried in the less efficient and therefore very lightly loaded plant. Reserve which amounts to but 25 to 50 per cent of the load being carried is simply a problem of keeping turbines and boilers loaded slightly below their most efficient point. The problems of operation become accentuated only as the reserve exceeds this limit, and it is the standby plant carrying minimum load and maximum reserve that best illustrates the factors involved.

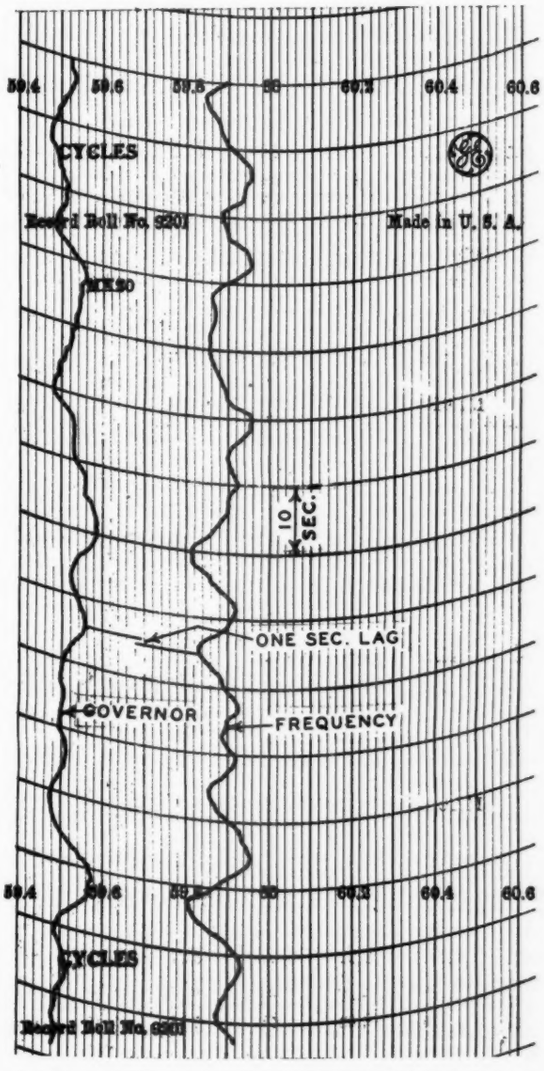

Fig. 2—Chart from no-lag frequency recorder with accompanying record of governor reaction. Governor line moves toward frequency line as frequency falls.

Such a case will be considered in this paper. Cahokia, a plant of 235,000 kw. capacity, originally designed for base load operation but recently connected in parallel with a newly built hydro-electric plant, has been operated at 18,000 kw. load with the reserve set at 45,000 kw., the possible load being estimated at 63,000 kw. The loss of a transmission line into the plant or any similar trouble on some 480 miles of interconnecting transmission lines may cause as much as 60,000 kw. of generator load to drop onto the balance of the system. The factors involved are so complex it is never certain as to how the plants involved will automatically redistribute the system load. In view of governor studies made along the lines already described it was decided that the bulk of this 60,000 kw. would fall on Cahokia, but with a low frequency alarm set at 59.4 cycles in all plants the operators could act quickly enough to limit the Cahokia load to 63,000 kw.

The effect of this 45,000 kw. load pick-up is shown graphically in Fig. 3. Two turbines must be operated in this station, because they are necessary for satisfactory system dependability and to supply internal reserve to the extent that one unit could maintain the load and keep the station on the system frequency in case the other "kicked out." For reasons of station heat balance and switching layout a unit of 35,000 kw. and another of 50,000 kw. capacity are usually chosen, the resulting 85,000 kw. generator capacity being ample for reserve. Turbine manufacturers ordinarily establish 20 per cent of rated capacity as the minimum load for safe operation in order to avoid overheating of turbine blading. The station minimum load is thereby established at 18,000 kw., the load to be carried whenever an abundance of water for hydro plants brings up the possibility of wasting water. It must be emphasized that these conditions of minimum load and maximum pick-up are those established by equipment not designed for standby operation, and apply to a plant which it is expected will be operated as a standby plant not more than a few weeks a year. Mechanical changes which would permit greater flexibility of reserve and load are therefore not justified.

Ratio of Steam Demand Increase to Load. A plant load of 18,000 kw. establishes the output of the boiler room at 270,000 lb. steam per hr. This establishes the greatest number of boilers[3] at minimum rating that can be kept steaming, which in turn establishes the maximum amount of steam that can be generated and therefore the maximum load which the plant can carry during a fault, i.e., 63,000 kw. This follows from the fact that the boilers as now installed cannot be operated below a certain rating or increased beyond a certain rating under the rapidly changing conditions of a system fault. This also indicates why there would be no advantage in this particular plant for equipping turbines with steam by-pass, a device sometimes used to permit their carrying less than 20 per cent load. Banked boilers are relied upon only for relieving the other boilers from continued operation at high rating. Ordinarily they cannot be brought on the load and up to rating in less than ten minutes, by which time the emergency has either been successfully met or other provisions made for carrying the load.

Informing the Crews. At the time of a system fault there is frequently sufficient electrical disturbance to cause a definite change in the pitch of station noises which, to experienced men, is sufficient notice that something is wrong and that they should get to their posts at once. For standby operation there

[3] There are 19 boilers rated at 1801 boiler hp. without including water walls; they are of the B&W cross-drum type fired by a storage system or unit mill system of pulverized coal; some of the boilers are equipped with forced and induced draft fans and others rely on natural draft.

is great value in a low-frequency alarm, sounding at a fraction of a cycle below the ordinary range of frequency variation, on the switchboard and in the turbine and boiler rooms. This is equivalent to instructing the boiler operators to bring up boiler steaming ratings and light up banked boilers with all possible speed. Increasing of boiler ratings should be under way twenty seconds after the occurrence of the fault.

Boiler House Organization. With a station load of 18,000 kw. and a generator capacity of 85,000 kw. on load the usual practice is to have five boilers on load and two "hot banks" at no less than 265 lb. drum pressure, 80 lb. below the usual 345 lb. With this set-up the boilers are usually arranged so that no single furnace operator has more than four boilers to operate. The boiler room foreman takes up his position at the second elevation which is the control level for the storage system boilers which predominate in number. Each man moves to an assigned post and has certain duties to perform in a prescribed sequence. The first step is to build up load on the five steaming boilers and the next to light up the banked boilers. For increased steaming ratings the first step is to increase drafts and the next to increase fuel feed. The automatic combustion control equipment helps in this service but it functions on "contacts" about every five seconds. This is too slow to meet such emergencies, and assistance by manual control is essential. The increase in fuel feed requires that additional burners be placed in service on vertical, streamline-fired furnaces and then speeding up all feeders; on unit-mill-fired boilers, it requires increasing feeder speed and then putting the second of two mills into service. The operators then go from boiler to boiler making the necessary adjustments to increase ratings, the first increase in ratings being quickly obtained, the last step to maximum output requiring considerable time for critical adjustments. (Table II.)

TABLE II—FIRING DATA AT MINIMUM RATINGS

	Storage System Vertical Streamline	Storage System Horizontal Turbulent	Unit Mill Horizontal Turbulent
Steam flow; lb./hr.	40,000	57,000	62,000
Air flow (meter)	47,000	62,000	79,000
Draft, uptake, in. H_2O	0.05	0.08	0.18
" " furnace " "	0.02	0.02	0.02
Steam press. lb. gage	345	345	345
" temp. deg. fahr.	660	675	690
Heat liberation—B.t.u./cu. ft./hr.	4,630	5,830	7,020
Flue gas temp. deg. fahr. (blr. exit)	478	485	490
CO_2, per cent 1st pass	13.1	13.7	14.0
" " " 3rd "	12.8	13.4	13.6
No. of feeders or mills in service	5	2	2

FIRING DATA AT NORMAL RATINGS

	Storage System Vertical Streamline	Storage System Horizontal Turbulent	Unit Mill Horizontal Turbulent
Steam flow; lb./hr.	88,000	110,000	110,000
Air flow (meter)	88,000	110,000	110,000
Draft, uptake, in. H_2O	0.5	0.5	0.5
" furnace " "	0.05	0.05	0.05
Steam press. lb. gage	345	345	345
" temp. deg. fahr.	685	700	710
Flue gas temp. deg. fahr.	520	530	530
Heat liberation—B.t.u./cu. ft./hr.	10,200	11,250	12,450
CO_2, per cent 1st pass	14.0	14.5	14.8
" " " 3rd "	13.8	14.3	14.6
No. of feeders or mills in service	8	10	2

Banked boilers are kept about 80 lb. below line pressure so that they do not flash saturated steam into the steam headers as the boiler steam pressure drops. This is done by firing them intermittently about every two hours. The procedure for lighting up these boilers is the same as prescribed for safe starting of boilers under all conditions. The increase in demand for boiler feedwater is taken care of by auxiliary operators in the turbine room. In case the station supply of power for electric-driven auxiliaries fails certain station auxiliaries and certain auxiliaries for some boilers are equipped with dual steam drives which must be started.

After maximum ratings are reached, the operators concern themselves with such problems as slag, ash removal, slagging of generator tubes and take all the precautions necessary for prolonged operation at high rating. The banked boilers brought onto load assist by permitting lower ratings on the other boilers. Cold boilers will, of course, be brought on load

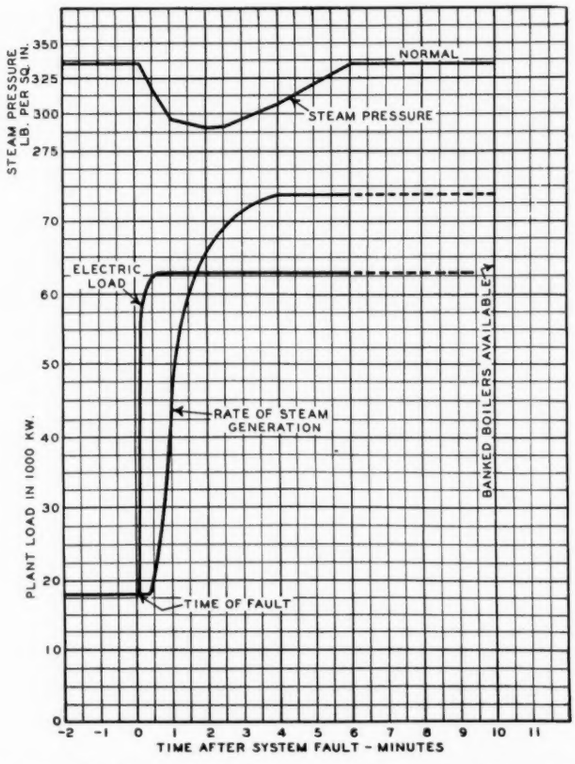

Fig. 3—Electric load, steam generation (but not steam flow) and steam pressure, following system fault. Steam generation lags behind steam demand resulting in drop in boiler pressure which is restored to normal as rate of steam generation exceeds steam demand. After point A load can be increased or rate of steam generation decreased.

if needed, but starting these requires $1^1/_2$ hr. If the steam pressure drops below 250 lb., from the original 335 lb., then the switchboard is called on to reduce loads because below this pressure emergency steam-driven equipment will not function properly.

Mechanical Capacity of Boilers for Greater Steam Release. Returning to Fig. 3 it may be seen that about 20 sec. are allowed for swinging the boiler room crew into action. There follows an interval up to three minutes before boilers reach their full rating as shown in Fig. 4. The heavier steam demand, however, has reached the boiler room about 12 sec. after the system fault and this demand exceeds the rate at which coal is being burned. The difference is made up by a drop in steam pressure. The amount of drop can be determined by a relatively simple calculation. If a boiler is producing 40,000 lb. of steam per hr. the equivalent heat output is at the rate of 12,000 B.t.u. per sec. Each 10-lb. increment of pressure represents a difference of 3.0 B.t.u. per lb. in heat content of the 110,000 lb. of water in the boiler. As the pressure drops 10 lb. there is, therefore, 330,000 B.t.u. released as latent heat for the formation of steam. A 10-lb. drop is equal to the 40,000 lb., original steam rate, for 27.5 seconds. It is this "reservoir" effect which enables the boiler to meet wide fluctuations in demand. The increased steam output is not all gain, however, since the quantity of gases passing over the superheater has not increased proportionately. The degrees of superheat therefore drops. From 50 to 90 fahr. of normal 250 fahr. superheat have been lost at Cahokia in this manner, which in turn increases the turbine water rate by 5 to 9 per cent. The net result is that 5 boilers generating 270,000 lb. steam per hr. and requiring 3 min. and 20 sec. to increase their output to 800,000 lb. per hr. can meet a demand for 720,000 lb. steam per hr. with a boiler steam pressure drop from 335 lb. to 290 lb. This pressure is gradually restored to normal at the end of about 6 min. At

the end of 10 min. when banked boilers are brought onto load and steam pressure is back to normal, the situation is amply cared for. The foregoing figures for pressure drop are extreme with instantaneous system fault and no more than ordinarily favorable boiler room performance.

Pulverized Fuel Combustion Conditions at Minimum Ratings. Carrying minimum rating on pulverized fuel-fired boilers offers a number of problems in firing and burning. Economy is not of the same importance as at normal ratings but, of course, must be considered. In general the most important problem in pulverized fuel firing for minimum rating is one of maintaining a sufficiently tight setting so that a slight furnace draft of 0.02 in. water can be maintained without admitting unwarranted amounts of excess air for the amount of fuel being fed. If a negative pressure is not kept in the furnace there is a tendency for the setting to "gas" and the heat "bottling" effect may result in much greater furnace maintenance. It is difficult to maintain 0.02 in. draft in the bottom of the furnace and obtain sufficient negative pressure in the upper section of the setting, necessary if the tendency to blow smoke, gas and dust out of the setting into the boiler room is to be avoided. Only with a tight setting can this be done. Beyond this common requirement the problem has been found to vary somewhat with the type of pulverized fuel firing, i.e., with (1) streamline firing from a storage system, (2) horizontal turbulent firing from a storage system, and (3) with unit mills and horizontal turbulent firing.

Referring to Table II it is seen that under low-load conditions, heat liberations of 4630 B.t.u. per cu. ft. per hr. are

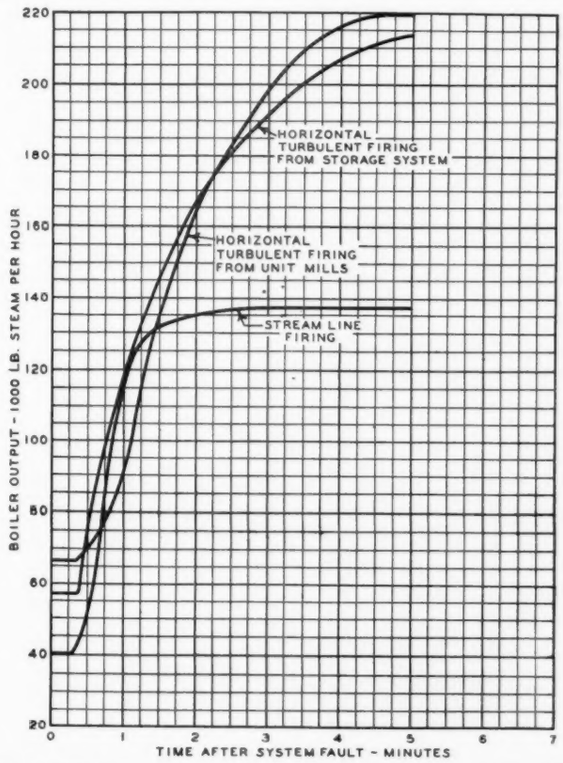

Fig. 4—Maximum rate of increasing boiler steam generation from minimum steam output on three types of firing.

maintained with about 1 per cent less CO_2 than in normal operation. For very low loads, corresponding to 70 per cent of boiler rating, all furnaces are operated with five of the ten burners in service. There is no serious difficulty encountered here except that some care must be given to choosing burners which must be in such condition as to minimize a tendency for laning of gases through the setting with consequent uneven combustion, poor efficiency and a possibility of eroding refractory walls.

In the horizontal turbulent type of firing where four large burners are used, a fixed quantity of primary air is needed to provide sufficient velocity to carry the coal through the transport pipe into the furnace. If the air is too greatly reduced and the velocity drops below a critical point, the coal settles out and is not delivered evenly in a turbulent state to the furnace. For this reason slightly higher ratings are carried on these furnaces than on those fired by streamline burners. The furnace heat liberation at 5830 B.t.u. is about 25 per cent greater than with streamline firing. The unit mill boiler is carried at still higher furnace heat liberation, 7020 B.t.u.; this is not inherent in this type of firing but is due to larger pulverized coal pipes which require greater air flow to support and carry the coal particles.

There has been no tendency at low ratings for slag to form in the furnace pit or to adhere to the lower boiler generator tubes. There is, however, a definite tendency for ash dust to settle out in larger quantities on the generator tubes and in the furnace so that a sudden increase in boiler rating with higher furnace heat liberation will cause the accumulation to fuse and run to the bottom of the furnace or adhere to the tubes.

Except for these limitations, boiler operation at low ratings does not result in serious difficulty or loss of economy. The greater excess air is about offset by considerably lower flue gas temperature, and the *steaming period* boiler efficiency is very nearly that of normal operation. The coal burned in maintaining a hot setting under banked boilers, however, increases and the *overall* boiler plant efficiency will be less.

The rate at which the output of these types of boilers can be increased is shown in Fig. 4. The factors which limit the rate at which furnace heat liberation can be increased are: (1) the limitation of crews available in making the necessary adjustments, (2) the speed with which motor-operated dampers, fuel feeders, and the like respond, (3) the necessity for cautious observance of water levels, and (4) the danger of flooding burners or mills with too rapid a flow of coal. The rate of combustion in the furnace will increase as rapidly as coal and air in combustible amounts are delivered, and there is, compared to the other limitations, little lag in the heat absorption and steam release cycle. The horizontal turbulent type of firing responds more rapidly because air and coal supply are increased at once and together. In the vertical type of firing with only 15 per cent of combustion air as primary air there is some lag because the increased stack draft must work back through the hollow refractory walls before sufficient air for combustion is available. Fuel feed in this case must be advanced cautiously for fear of flooding the furnace. On the other hand if the coal happens to be wet the feed to unit mills must be increased with caution to avoid plugging.

With the foregoing methods of minimum load and standby operation, substantial system savings have been possible over what might be called normal low-rating operation of the plant.

New Index to International Critical Tables Now Available

The new, complete index to *International Critical Tables* is now available. This index contains about 330 pages and matches the previous volumes in all details. Subscribers to *International Critical Tables* will undoubtedly desire to complete their sets by the addition of this valuable index. The price of this index is $4.00, and copies can be obtained from the National Research Council, Washington, D. C.

The Bigelow-Liptak Corporation, Detroit, Mich., announces the removal of its offices from 5057 Woodward Avenue to the Curtis Building, 2842 West Grand Boulevard.

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NEW EQUIPMENT

of interest to steam plant engineers

Compensated Air Cell for Potentiometers

A new type of battery has been developed by the Brown Instrument Company, Philadelphia, Pennsylvania. This battery enables the Brown Potentiometer Pyrometer to record or control temperatures accurately without the necessity of frequent standardizing.

This new battery, the Brown Compensated Air Cell, is a wet type non-rechargeable battery, which is shipped dry and rendered active by adding cool drinking water.

In addition to having a large ampere-hour capacity, the Brown Air Cell is equipped with a built-in coil which automatically compensates for changes in the temperature surrounding the battery. Therefore, regardless of temperature changes, the Brown Air Cell has a constant current output.

The constant current output feature of the Brown Air Cell is very important as the accuracy of every potentiometer pyrometer is dependent on its source of constant current.

Another feature claimed for this cell is its large ampere-hour capacity. This insures a constant current output over long periods of time and eliminates the necessity of frequent standardizing. This battery includes an internal automatic temperature compensator (patent pending) which corrects the temperature coefficient of the cell and maintains a constant current output regardless of changes in surrounding atmospheric temperature. The life of the Brown Air Cell is claimed to be over two and one-half years.

Rubber-Lined Valve

Designed for handling corrosive and abrasive fluids under conditions of fairly high pressure, pulsating pressure, throttling or suction, a new rubber-lined valve of simple, rugged design known as the Vulcalock valve is announced by The B. F. Goodrich Rubber Company, Akron, Ohio.

The new valve may be lined with any of the standard Goodrich Acidseal rubber compounds, hard or soft, depending upon conditions of service. This valve is expected to solve the problem of handling corrosive or abrasive fluids.

Action of the valve does not depend upon a flexible diaphragm. The resilient, rounded disc which snaps over a circular plate at the lower end of the stem provides an absolute seal when brought into contact with the molded rubber-covered seat.

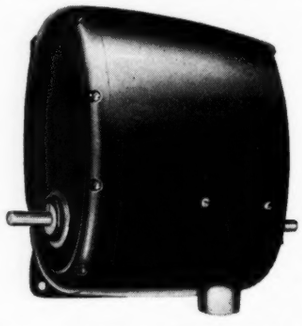
Both disc and ring are simple, inexpensive, easily replaceable parts. A steady, uniform flow with positive shut-off is obtained under severe operating conditions. The valve can be used for vacuum and throttling work.

Unique engineering features listed by the manufacturer are: Acidseal lining of valve bonded to metal parts with practically integral adhesion by patented Vulcalock process—corrosive or abrasive materials come in contact only with rubber especially designed to resist their deteriorating action—nearly straight line of flow makes the valve especially adaptable to fairly high pressure work and abrasive service—on sizes up to and including 6 inch, there is no restriction of flow through the seat ring—resilient molded disc which snaps over circular plate at lower end of stem readily replaceable at very low cost—molded seat ring, double seated and reversible for double service, can be easily removed.

Industrial Motors

A new line of industrial motors has recently been developed and placed on the market by the Minneapolis-Honeywell Regulator Company, 2710 Fourth Avenue, South, Minneapolis, Minnesota.

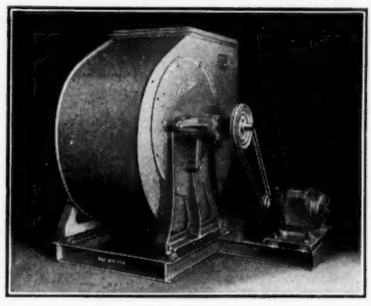
These power units are inherently electric motor driven speed reducers in that each incorporates a motor element and reduction spur gear trains. The assembly is a compact, strongly built one to withstand continuous duty service. They may be used in conjunction with Minneapolis-Honeywell controlling devices or with those of others, including the products of pyrometer manufacturers and are available for operation in accordance with the following modes of automatic control: two-position—on and off—high-low—three position—floating and proportioning.



As these motors are adaptable to damper regulation and as their electrical circuit can be easily inter-connected with their motorized Minneapolis-Honeywell fuel-air valves, this company can supply equipment which serves not only to regulate industrial furnace temperature but also to adjust its atmosphere. Among many other usages for this motor is the direct drive of double seated regulating valves of the sliding and rotary shaft stem classifications in a wide range of sizes serviceable in the power, district steam, and all industrial processing fields in conjunction with automatic controllers or remote station switches.

Quiet Fan with Silent Base

A new quiet ventilating fan has recently been designed and placed on the market by the Buffalo Forge Company, Buffalo, New York. To further insure the silent qualities of this fan equipment the Buffalo Floating Base has also been designed. This provides what is claimed to be a practical, inexpensive means of insulating a fan and its driving motor from the building foundation. Flexible rubber insulators are so applied as to eliminate metal contacts between the bolts holding down the base and the fan and thus providing a damping effect.



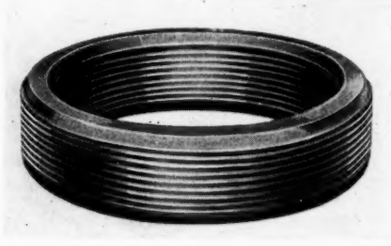
The rubber used in these insulators is placed "in shear" rather than "in compression" which, it is claimed, maintains the life of the rubber over a long period.

This fan unit is especially applicable where quiet operation is of importance

New Packing for High Steam Pressures

Yarnall-Waring Company, Philadelphia, Pa., has developed a new form of laminated packing for use in Yarway Seatless Blow-off Valves. This packing consists of several stainless steel rings with long fiber asbestos packing between them. At the time of assembly the mass is compressed and heat treated, so that the finished ring is a complete unit suitable for high pressures and temperatures. A very slight clearance is maintained between the metal laminations and the valve plunger.

In the company's high-pressure steam research laboratory, the new packing rings have been subjected to blow-down tests at various steam pressures, ranging from 450 lb. to 2100 lb. The tests were conducted with valve throttled, so that the operating conditions were more severe than those encountered in normal blow-down service. Compared with similar tests on the armored packing rings previously used in these valves, the tests on the new laminated packing showed that the new construction practically eliminates blow-down leakage, even at pressures as high as 2100 lb. and under the throttling service mentioned above.



REVIEW OF NEW TECHNICAL BOOKS

Any of the books reviewed on this page may be secured from In-Ce-Co Publishing Corporation, 200 Madison Avenue, New York

The Calculation of Heat Transmission

By Margaret Fishenden and Owen A. Saunders

HEAT transmission problems are involved in most industrial processes at one stage or another. In some, the first consideration is to save heat; in others, the heat used is a small matter compared with the quality of the finished product, to which a proper distribution of heat may be vital. A working knowledge of the principles of heat flow and of the laws and numerical coefficients applicable to different cases is, therefore, highly important to the engineer and industrial technologist.

The Calculation of Heat Transmission by Dr. Margaret Fishenden and Owen A. Saunders of England was prepared under the auspices of the Fuel Research Board of the Department of Scientific and Industrial Research. In it an attempt is made to bring together in accessible form the various experimental results described in the mass of scattered literature now available on the subject. Complicated theory and specialized technical applications have been avoided, but, wherever feasible, results have been interpreted and compared in the light of fundamental principles of conduction, convection, and radiation.

The subject is a complicated one, due partly to the difficulty of defining conditions and partly to the fact that the experiments as yet carried out are far from covering the effects upon the heat transmission of all possible variable factors, and it will be evident to the reader that there is room for much further experimental work. Nevertheless, since even rough calculations may be of great practical assistance, the authors have given numerical values of heat transfer coefficients for as wide a range of conditions as possible so that the engineer can work out his problems for himself.

The main chapter headings are as follows: Radiation; Calculation of Radiation Heat Transfer; Emission and Absorption of Radiation by Gases and Flames; Conduction; Calculation of Conduction Heat Transfer; Convection; Natural Convection in Gases; Forced Convection in Gases; Convection in Liquids; Heat Transfer Calculations.

The book is well illustrated and contains 280 pages, $5^3/_4$ x $9^3/_4$, including a comprehensive bibliography, and name and subject indexes. Price $2.50.

International Handbook of the By-Product Coke Industry

By Dr. W. Gluud
American Edition by D. L. Jacobson

SEVERAL years ago a two-volume handbook of the by-product coke industry, by Dr. W. Gluud, appeared in Germany. Since the working methods, scientific principles, and technical details of this industry are virtually the same the world over, it was decided that it would be desirable to make this German edition into an international handbook. The author, who has been in charge of the Gesellschaft für Kohlentechnik at Dortmund for nearly fifteen years, is a leading authority in the by-product coke industry, and was therefore very well qualified to undertake this task.

The publication of the American and English editions of this book, which are practically identical, was made possible by the whole-hearted cooperation and untiring efforts of the late D. L. Jacobson of the Koppers Company in America and E. M. Myers of the Dorman, Long & Co., Ltd. in England. The entire book has been revised, brought up to date, and additions of interest to American and British readers made.

To the American reader, the outstanding value of this book will be its wealth of particulars relative to European theory, invention and experience, which has hitherto been generally unavailable here. Much of the descriptive material concerning American and English practice has never previously appeared in book form anywhere. In presenting this material, the primary objective has been to draw a complete picture of the international by-product coke industry. No attempt has been made to include information of a subordinate nature fully familiar or readily available in this country. Thus, the common methods of testing used in every laboratory and completely described in the Gas Chemist's Handbook or in the publications of the American Society for Testing Materials are omitted, while the European methods appearing in Dr. Gluud's original "Handbuch" have been translated in full.

This book, profusely illustrated, contains 880 pages, size 6 x 9, including an index of authors and a subject index. Price $15.00.

Modern Methods in Quantitative Chemical Analysis

By A. D. Mitchell and A. M. Ward

THE authors offer in this book a critical selection of methods from the bewildering mass of literature available on the subject of analytical chemistry. It is intended that this book should function as a supplement to more standard works by including those methods which have been introduced or perfected within the last decade or so, but electrometric and other physical methods are not included since the description of the technique involved, e.g. in the use of azeotropic mixtures, is precluded by consideration of space.

In the selection of material, those methods have been chosen which most nearly fulfill the following requirements: (1) if involving the use of a Gooch crucible, they should preferably be adapted to the pattern having the sintered-glass diaphragm; (2) they should not depend upon a narrow range of empirical conditions or upon standardization under identical conditions; (3) they should be capable of effecting useful separations, and not be merely academic exercises in the estimation of simple substances; (4) the necessary reagents should be readily obtainable.

This book contains 178 pages, including index, size 5 x $7^1/_2$. Price $1.75.

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A modern type of Boiler Tube of steel or rust-resisting Toncan Iron, made by electrical resistance welding.

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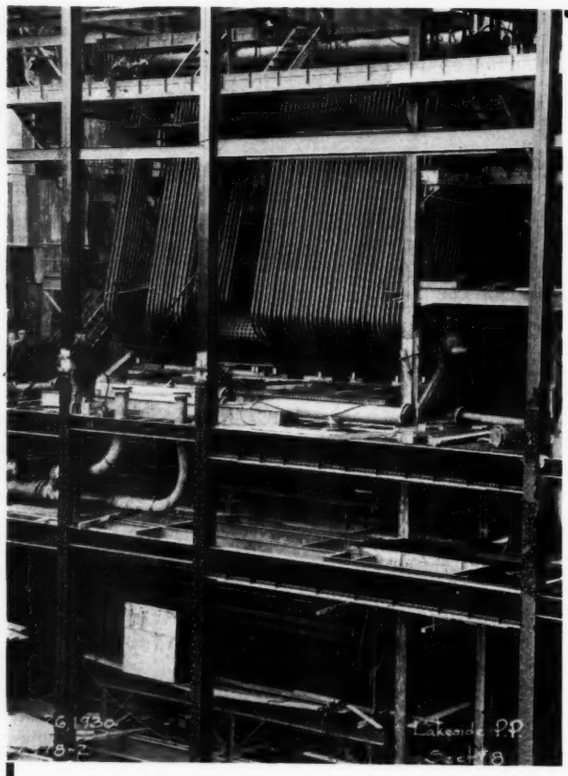

Globe tubes being installed in 1400-lb. pressure boiler, Lakeside Station, The Milwaukee Electric Rwy. & Light Company

GLOBE SEAMLESS STEEL BOILER TUBES

have been used in the most recently installed boilers at such notable plants as,

Hudson Avenue Station, Brooklyn Edison Company (over 50 miles of Globe bent boiler tubes were used in the recent extension of this plant)
Central Heating Plant, Washington, D. C.
East Port Washington Station, The Milwaukee Electric Rwy. & Light Company (being installed)

Globe Products are made to meet exacting specifications as to gage, surface, bends, etc.

•

Globe Seamless Tubes are available in regular carbon, copper content steels, nickel steels and chrome and chrome nickel alloys.

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